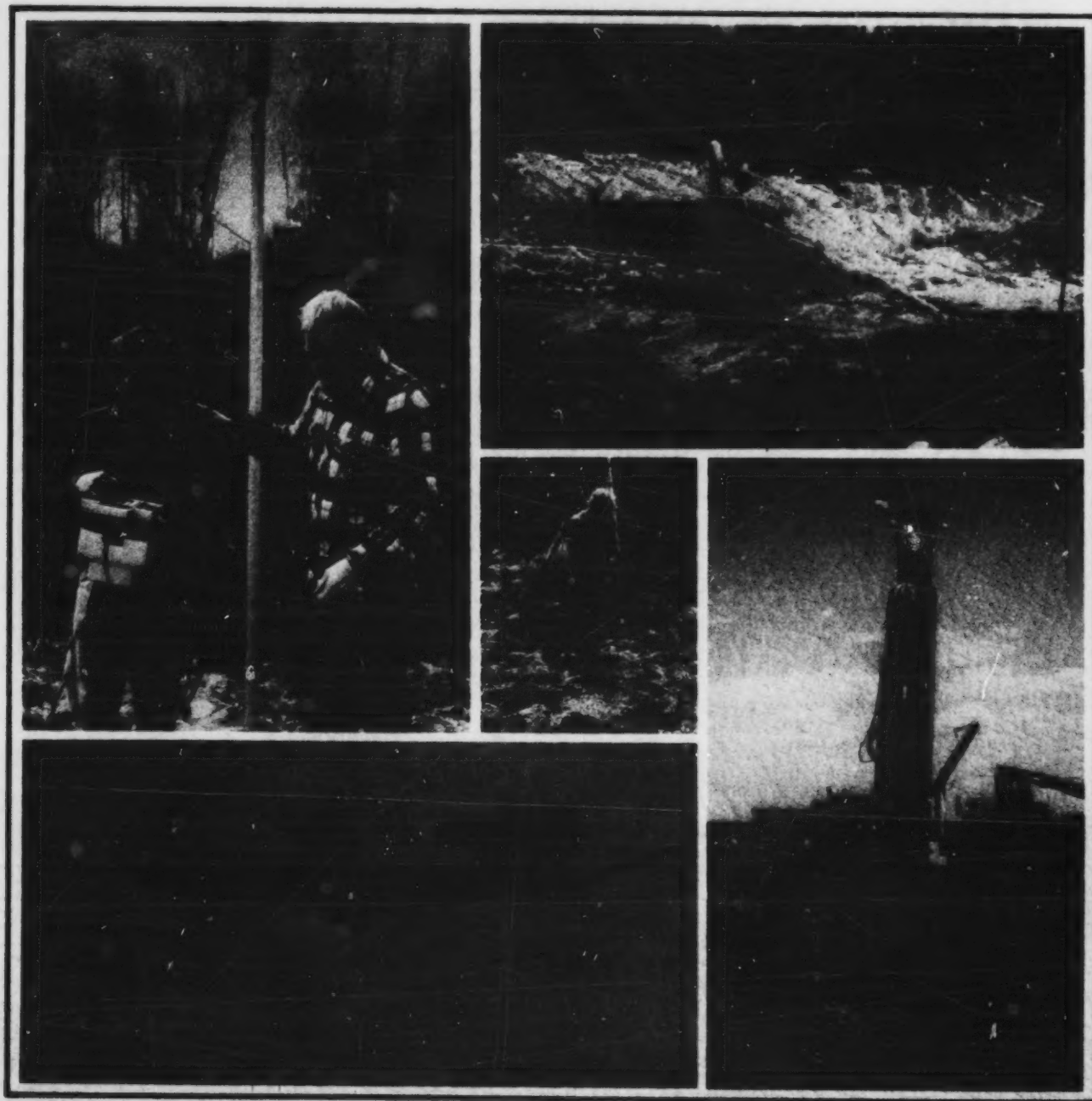


MODERN EXPLORATION TECHNIQUES



Special Publication Number 10

Proceedings of a Symposium held in Regina, November 20 and 21, 1989

92-02515/

MODERN EXPLORATION TECHNIQUES

**Proceedings of a Symposium
Held in Regina, Saskatchewan
20 - 21 November, 1989**

**EDITORS
L.S. BECK and C.T. HARPER**

**PRODUCTION EDITOR
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**SPECIAL PUBLICATION NUMBER 10
SASKATCHEWAN GEOLOGICAL SOCIETY
P.O. BOX 234
REGINA, SASKATCHEWAN, CANADA
S4P 2Z6**

1990

COVER:

Cover illustrations depict a variety of techniques currently used for mineral exploration; clockwise from upper right they are: 1) in drift covered areas of the Shield large scale stripping and sluicing of outcrops has greatly aided geological interpretations and structural studies of ore deposits (photo by C.T. Harper); 2) rotary drilling in the Fort a la Corne area of east-central Saskatchewan to obtain bulk samples for diamond exploration (photo by P. Reeves); 3) airborne geophysical surveys continue to play a leading role in identifying targets for mineral exploration (photo courtesy of Questor Surveys Ltd.); 4) a common follow-up to airborne geophysics are ground geophysical surveys, such as this magnetic survey (photo by D.G. MacDougall); 5) boulder prospecting and lithogeochemistry is a fundamental exploration technique for Athabasca Basin uranium deposits, but is applicable to all glaciated terranes (photo by C.T. Harper). Cover design by C.T. Harper.

Canadian Cataloguing in Publication Data

Main entry under title:

Modern exploration techniques: proceedings of a
symposium ...

(Special publication/Saskatchewan Geological
Society; no. 10)

"Proceedings of a symposium held in Regina,
Saskatchewan, 20-21 November, 1989."

ISBN 0-921547-18-8 (bound) - ISBN 0-921547-19-6
(pbk.)

1. Prospecting - Congresses. 2. Prospecting -
Saskatchewan - Congresses. 3. Mines and mineral
resources - Saskatchewan - Congresses. 4. Geology -
Saskatchewan - Congresses. I. Beck, L.S.
II. Harper, C.T. III. Richmond-Johnson, N. (Nancy).
IV. Saskatchewan Geological Society. V. Series:
Special publication (Saskatchewan Geological
Society); no. 10.

TN270.A1M64 1990 622'.1 C90-097196-7

ISBN 0-921547-19-6

Copyright 1990

Publisher:

Saskatchewan Geological Society
P.O. Box 234, Regina, Saskatchewan, S4P 2Z6

This publication was prepared on Ventura DeskTop
Publisher. Formatting and layout by N. Richmond-
Johnson and C.T. Harper, Saskatchewan Energy and
Mines, 1914 Hamilton Street, Regina, Saskatchewan,
S4P 4V4.

Printing and binding:

Printco Graphics Inc.
1450 Hamilton Street, Regina, Saskatchewan
S4R 8R3

FOREWORD

This volume contains 15 papers, 3 extended abstracts and 11 abstracts based on poster papers and oral presentations made to 257 delegates attending a conference: 'Modern Exploration Techniques', held in Regina on November 21-22, 1989, and hosted by the Saskatchewan Geological Society.

The conference was divided into four, half-day sessions; General Exploration and Geochemistry (including a paper on base-metals), Uranium, Diamonds, and Gold and reflects the diversity of commodities being explored for in Saskatchewan at the present.

Northern Saskatchewan ceased to be known solely as an 'uranium province' in 1987 when, for the first time since the mid nineteen-forties, annual exploration expenditures for precious and base-metals surpassed those for uranium. With a mature uranium industry, an emerging gold sector, high levels of activity for diamonds, as well as interest in platinum, rare earths and a variety of industrial minerals, the conference and proceedings volume serve as a valuable update of the Saskatchewan mineral exploration scene.

I would like to express my thanks to the authors for their cooperation in meeting deadlines and for their efforts in providing high-quality papers. Several Society members undertook the technical editing and their assistance is much appreciated.

This volume was produced by desk-top publishing software and laser printer and I would like to express my gratitude to Charlie Harper and Nancy Richmond-Johnson for their efforts in achieving high standards. I also wish to acknowledge the valuable assistance of Saskatchewan Energy and Mines for providing the staff time and resources required to expedite the publishing process.

L.S. Beck
Saskatchewan Energy and Mines

EDITORS' COMMENTS

- Editorial changes have been carefully made to try to avoid altering authors' original meanings, both factual and interpretative.
- Most illustrations are reproduced as submitted; unfortunately, a few lack complete clarity, especially if certain patterns of mechanical ornamentation were used on figures that required substantial reduction in size.

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- Semi-monthly meetings (September to May), each featuring a distinguished geoscience lecturer
- Biennial symposia, generally with themes which focus on different aspects of Saskatchewan's economic geology
- Special publications, mostly symposia proceedings, but including field excursion guides, geological highway maps (an upcoming project) and other miscellaneous studies
- Field trips
- Partial sponsorship of science fairs throughout the province
- Talks to grade-school and high-school students, upon request
- Occasional public lectures
- Annual awards to the most promising earth sciences undergraduate at the Universities of Saskatchewan and Regina
- Annual Christmas lecture for Regina school students featuring a distinguished Canadian geoscientist
- Award for the best student poster display at the annual Saskatchewan Energy and Mines Open House

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Corporate support is an important source of Saskatchewan Geological Society funds, and enables the Society to maintain vigorously its wide variety of geoscientific activities. Such support is also valuable in that it confirms to individual members that our goals are shared by industry. The Society therefore acknowledges with deep gratitude the contributions it has received from the organizations listed above (Corporate Membership, \$100.00; Corporate Sponsorship, \$50.00; Corporate Donorship, \$25.00), and encourages others to join their ranks.

*Awarded by the S.G.S. Executive in acknowledgement of services rendered that greatly exceed in value the fee for the appropriate category of corporate support.

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General Exploration and Geochemistry

FINDING MINES IN SASKATCHEWAN: AN ANALYSIS OF THE ECONOMICS OF MINERAL EXPLORATION IN SASKATCHEWAN AS COMPARED TO OTHER PARTS OF CANADA

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ABSTRACT

This paper analyzes discovery success for uranium, base metals, gold and the industrial minerals in Saskatchewan over the period 1946 - 1989. All available records of mineral discoveries and company exploration spending are used to compare the discovery history in Saskatchewan with that in the remainder of Canada. This comparison is made for each metal or commodity group studied, both in terms of proportional amounts discovered and in relation to exploration expenditures for each of them.

INTRODUCTION

This paper presents the results of an analysis of mineral exploration success in the Province of Saskatchewan. It concentrates on, but does not confine itself to, the period beginning in 1946 when Canadian mineral exploration expenditure data first began to be gathered by the Dominion Bureau of Statistics (now Statistics Canada). Such exploration expenditure data is very useful in the comparison of exploration success for various mineral commodities in Saskatchewan with exploration success for the whole of Canada.

EXPLORATION EXPENDITURES IN SASKATCHEWAN

Figure 1 shows annual (non-petroleum) exploration expenditures for Saskatchewan over the period 1946 to 1987, both in current dollars and in constant 1988 dollars. Figure 2 shows Saskatchewan exploration expenditures as a percentage of total Canadian exploration expenditures over the same period. Comparison of Saskatchewan uranium exploration expenditures gathered by Energy, Mines and Resources (EMR) since the 1970s (Figure 3) with total exploration expenditures (Figure 1) indicates that in some years uranium exploration expenditures appear to have exceeded total exploration expenditures. This is clearly impossible and demonstrates the incompleteness of some of these statistics. Nevertheless, despite such

unavoidable inaccuracies, the general exploration expenditure picture presented in Figure 1 is, in the author's opinion, a reasonable portrayal of reality.

The conclusions to be drawn from Figures 1 and 2 are: (1) relative to the rest of Canada, annual Saskatchewan non-petroleum exploration spending was relatively insignificant before the mid 1950s, and (2) relative to Canadian exploration expenditures of more recent years, annual exploration spending in Saskatchewan remained at very low levels until the late 1960s.

EVALUATION OF SASKATCHEWAN MINERAL EXPLORATION SUCCESSES

Mineral exploration success in Saskatchewan can best be evaluated by considering various mineral commodities or groups of commodities separately. Exploration geologists who work in the Canadian Shield tend to overlook the importance of what are commonly called the 'industrial minerals', perhaps because most have not had experience exploring for those mineral commodities. However, because of their considerable economic significance, they can't be ignored when evaluating the mineral discovery success in Saskatchewan. In addition to structural materials such as sand, gravel, other mineral aggregates, building stone, raw materials for cement and the like, Saskatchewan has major reserves and

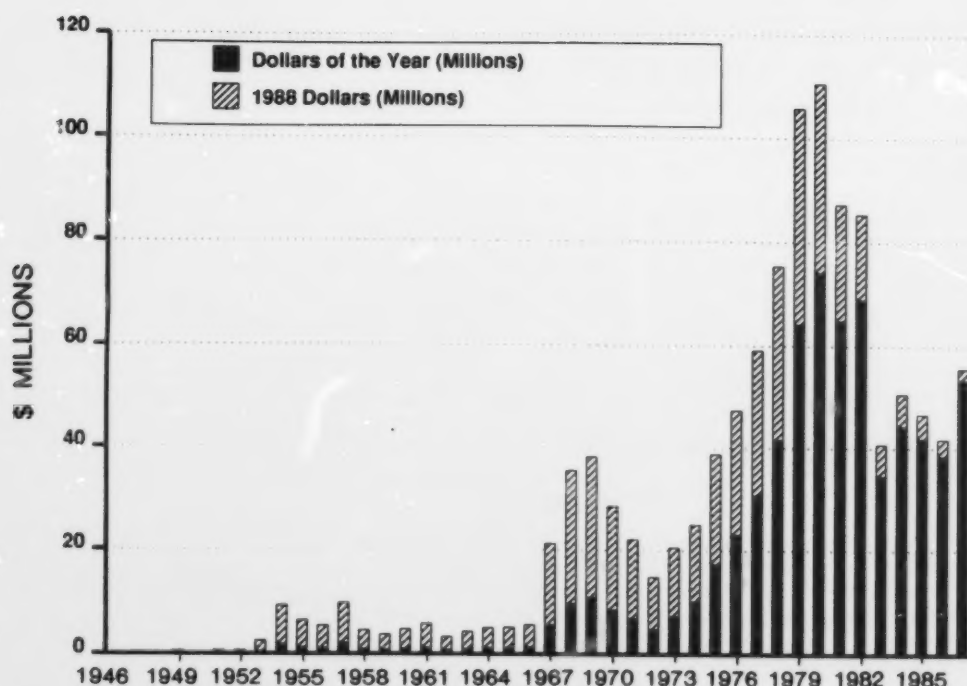


Figure 1 - Exploration expenditures in Saskatchewan, 1946 - 1987. Sources: 1946 - 1963 - Statistics Canada 'Prospecting' Expenditures; 1964 - 1966 - 'Prospecting' expenditures compiled by EMR from original Statistics Canada questionnaires (these totals were never published by Statistics Canada); 1967 - 1979 - Statistics Canada 'Physical Work and Surveys'. Overhead expenditures (land costs, administrative expenses in the field and exploration-related head office expenses) have been compiled by EMR from the original questionnaires received from companies by Statistics Canada and added to 'Physical Work and Surveys'; 1980 - 1986 - Statistics Canada catalogue 61-216; 1987 - derived by EMR from Statistics Canada catalogue 61-216 and Federal-Provincial Exploration Survey questionnaires.

resources of sodium sulphate, potash and sodium chloride (common salt).

Sodium Sulphate

Sodium sulphate was first produced from alkaline lakes in southern Saskatchewan in 1919. In addition to the approximately 20 Mt that have already been produced since then, these lakes contain reserves of 90 Mt of sodium sulphate, some 51 Mt of this in 21 individual deposits each containing 500,000 tonnes or more.

Potash

Sodium sulphate reserves appear insignificant when contrasted with the potash reserves of the Middle Devonian Prairie Evaporite Formation (Table 1). This potash and the enormously greater quantities of halite (common salt) that underlie it were discovered essentially by accident by Imperial Oil when that company was drilling for oil in the early 1940's. Potash has been produced in Saskatchewan since 1958, and the province has become one of the world's major producers.

Table 1 - Potash reserves of Saskatchewan contained in the Prairie Evaporite Formation (Source: Zwartendyk, 1989).

- ° Recoverable by conventional mining to a depth of About 1 100 m
14 billion t K₂O equivalent, or
23 billion t KCl
- ° Recoverable by solution mining below 1 100 m
42 billion t K₂O equivalent, or
69 billion t KCl
- ° Total recoverable above and below 1 100 m
56 billion t K₂O equivalent, or
92 billion t KCl

Halite

Even 92 billion tonnes of recoverable KCl is relatively insignificant compared with the approximately 90 trillion tonnes of halite that underlie it. This enormous halite resource consists of over a hundred metres of pure white halite. The tonnage, which is only approximate, was calculated using conservative assumptions regarding the lateral extent of the halite.

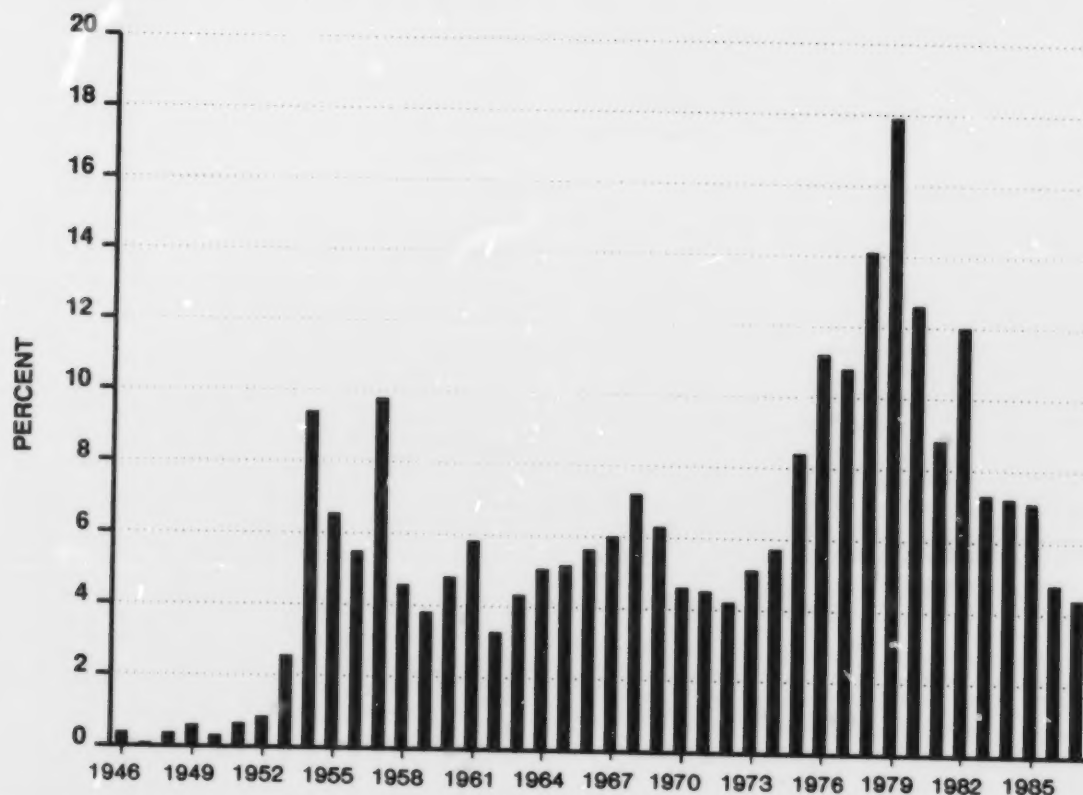


Figure 2 - Exploration expenditures in Saskatchewan as a percentage of total Canadian exploration expenditures, 1946-1987. Sources: calculated by EMR from the same sources as 'Mineral Exploration Expenditures in Saskatchewan', 1946-1987.

There isn't, of course, a large enough market for that much halite, which is perhaps a good thing because the surface subsidence that would result from mining of this vast tonnage might turn much of southern Saskatchewan into a very large lake. But all of the halite that anyone could possibly expect to use is available from the Prairie Evaporite Formation alone. Although by far the largest, the Prairie Evaporite Formation is not the only formation containing halite in Saskatchewan.

Salt has been produced from the Prairie Evaporite consistently since 1949 with minor intermittent production prior to that time. Saskatchewan production has been about 400 000 t/y in recent years.

Coal

Saskatchewan has about ten per cent of Canada's coal resources. Some 12.2 million tonnes of lignite, valued at \$122 million were mined in Saskatchewan in 1987, nearly all of it used for thermal generation of electricity.

Table 2 - Coal resources of Saskatchewan (lignitic sub-bituminous). Source: Smith (1989).

Measured	1 455 Mt
Indicated	2 690 Mt
Inferred	3 460 Mt
Total	7 595 Mt

Uranium

Large quantities of uranium have been discovered in Saskatchewan over the 41 years that have passed since 1948, when Eldorado Mining and Refining (1944) Limited (Eldorado) discovered the orebody that became the Ace mine, at Beaverlodge Lake, Saskatchewan.

The Uranium and Nuclear Energy Branch of EMR has gathered company data on Canadian uranium exploration expenditures beginning with the year 1971. The industry has co-operated fully with this survey, so that very good uranium exploration expenditures have been available for Saskatchewan since 1975. Unfortunately, only Canadian exploration spending totals are available for uranium for the years 1971 to

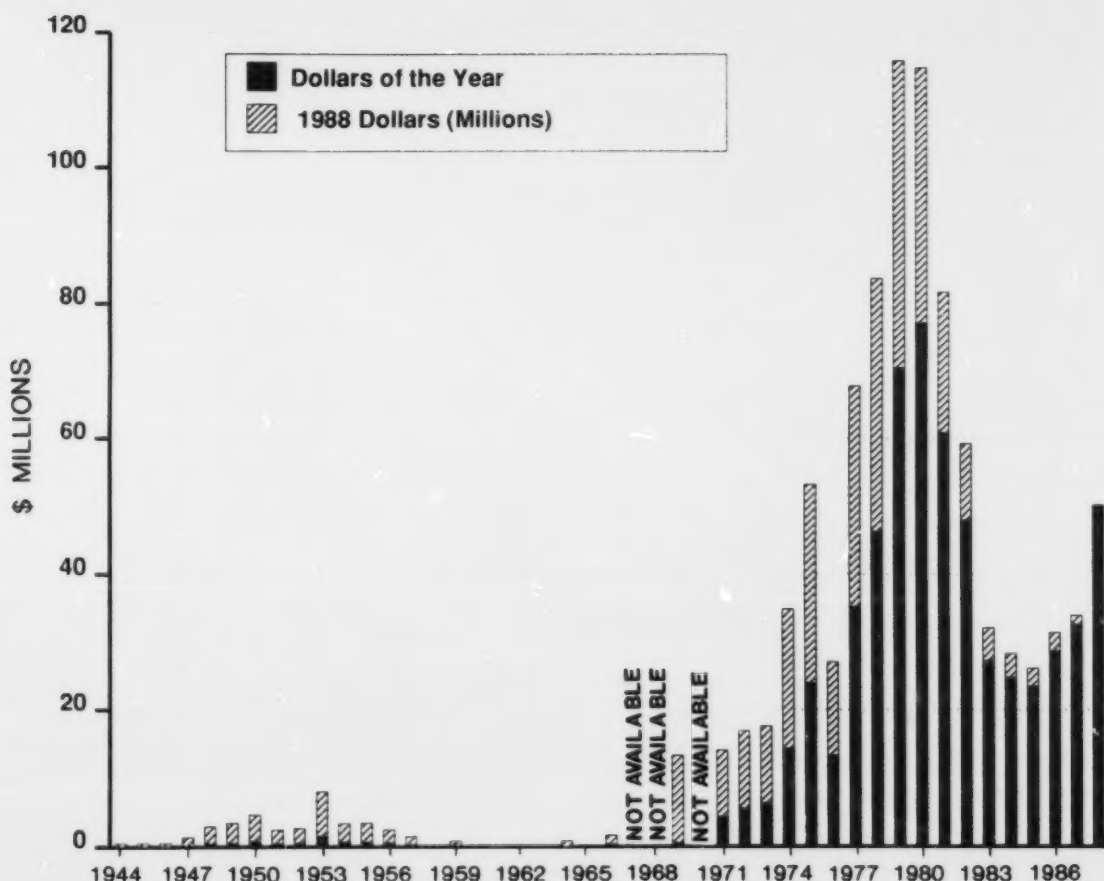


Figure 3 - Uranium exploration expenditures in Saskatchewan, 1944-1988. Sources: 1944-1971 - derived by D.A. Cranstone, EMR, using: 1. individual company exploration questionnaires returned to Statistics Canada, 2. company reports to shareholders, and 3. information in various Saskatchewan Government publications; 1972-1988 - EMR's annual uranium exploration questionnaire, assuming that for 1972-1975, 50% of Canada's uranium exploration expenditures were in Saskatchewan.

1974 inclusive. Therefore, to come up with Saskatchewan uranium expenditure estimates for those years, based on what we know about historical Canadian uranium exploration activity, the assumption was made that half of Canadian uranium exploration expenditures were made in Saskatchewan during that period.

To determine annual uranium exploration expenditures for the period 1944 (when exploration for uranium began in Saskatchewan) to 1970 presented a somewhat greater challenge. Eldorado was the only company allowed by law to explore for uranium in Canada during the years 1944 to 1947 inclusive. Saskatchewan uranium expenditures for those four years were derived on the basis of information in Eldorado's annual reports. This left the 23 years 1948 to 1970 as unknowns. It proved possible to compile reasonably accurate uranium exploration expendi-

tures for all but three of those years using data from five principal sources:

1. Company annual exploration expenditure data for Saskatchewan gathered, at the time, from each company by Statistics Canada's annual surveys of Canadian mineral exploration expenditures.
2. EMR's Corporate Records Files maintained by the Mineral Policy Sector, which contain a nearly complete set of company annual reports, securities and exchange prospectuses, clippings of articles from the mining publications and much other useful data.
3. The Northern Miner's annual Canadian Mines Handbooks covering the period 1944-88.
4. EMR's National Mineral Inventory Records maintained by the Mineral Policy Sector.

5. Various Saskatchewan government mineral industry reports.

Statistics Canada exploration questionnaires for the years 1967, 1968 and 1970 could not be located, so it proved impossible to come up with realistic figures for Saskatchewan uranium exploration expenditures for those three years.

Figure 3 shows annual expenditures on uranium exploration in Saskatchewan from 1944 to 1988. It gives a reasonably accurate portrayal of uranium exploration expenditures in the province with the exception of the years 1967, 1968 and 1970 (which, as explained above, are not available). The problem with the 1988 exploration total is that it includes \$20 million or more of test mining at the Cigar Lake and Midwest Lake uranium deposits. Although these expenditures have been counted as exploration in the EMR annual survey, the underground programs appear to have been related entirely to test mining, without any sort of exploration component.

Uranium Discovery Costs

Table 3 shows uranium exploration expenditures for Saskatchewan compiled for three periods, 1944-1970, 1971-1983 and 1984-1988 and the quantities of uranium discovered during the first two of these periods. Although not all the uranium would have been economically mineable at the low uranium prices of recent years, nearly all of it could have been economically mined at some time during the 1944 to 1988 period.

Discovery costs in Table 3 are calculated using only total exploration expenditures for a given period divided by the number of kilograms of uranium discovered during that period. No allowance is made for interest costs on exploration expenditures over the period from when the exploration costs were incurred until the year the uranium was, or will be, produced and sold.

Table 3 - Uranium discovery costs in Saskatchewan (1988 Canadian dollars per kilogram uranium discovered).

	1944-1970	1971-1983	1984-1988
U Explor. Expend. (1988 Can\$)	\$84 500 000	\$654 000 000	\$170 000 000
U Discovered (tonnes)	48 000	383 800	N/A
Discovery Costs (per kg)	\$1.76	\$1.70	N/A

Sources: For 1944-70 and 1971-83; from Cranstone and Whillans, 1989, recalculated to 1988 dollars; for 1984-88, Uranium and Nuclear Energy Branch, EMR.

Although the cost per kilogram of uranium discovered during the 1971-83 period (\$1.70) was only slightly lower than that for the 1944-70 period (\$1.76), the average grade and economic attractiveness of typical deposits discovered in the 1971-1983 period was much higher.

No serious effort was made to calculate quantities of uranium discovered in Saskatchewan during the 1984-89 period, because much of the data needed is not yet available. Indications are that substantial quantities of uranium have been discovered over that period. Preliminary information suggests that during the 1984-89 period discovery costs have probably not been very much higher than those of the 1946-70 and 1971-83 periods and that the average grades of the deposits discovered have been high.

Over the period 1971-88, Saskatchewan has been the place to explore for uranium in Canada. No other province or territory comes close to matching Saskatchewan in terms of low uranium discovery costs (Table 4) or in terms of high average grades of the uranium deposits discovered.

Table 4 - Uranium discovery costs in Saskatchewan compared to the remainder of Canada, 1971-83 inclusive (1988 dollars per kilogram of uranium discovered). Source: Cranstone and Whillans, 1989, recalculated to 1988 dollars.

Saskatchewan	\$1.70
Remainder of Canada	\$15.11

Base Metals and Gold

Saskatchewan appears to have been an excellent place to explore for the industrial minerals, coal and uranium. The evidence is somewhat different for base metals and for gold. Figure 4 shows exploration expenditures in Saskatchewan for the base metals and precious metals over the period 1946-87, compiled from company information available from the sources listed in the section on uranium. For 1975 and later years, government exploration questionnaires have asked companies to specify the mineral commodities for which they were searching. This has made it possible to differentiate exploration expenditures for base metals from those for precious metals for those years.

In Saskatchewan, precious metals expenditures have been, with rare exceptions, aimed at gold. For the 1946-74 period, it proved to be impossible to separate base-metal exploration expenditures from those for gold, chiefly because most large Canadian mining companies that explored in Saskatchewan have provided few public details on what commodities they were searching for during those years. The available information makes it clear that a significant amount of gold exploration was carried out

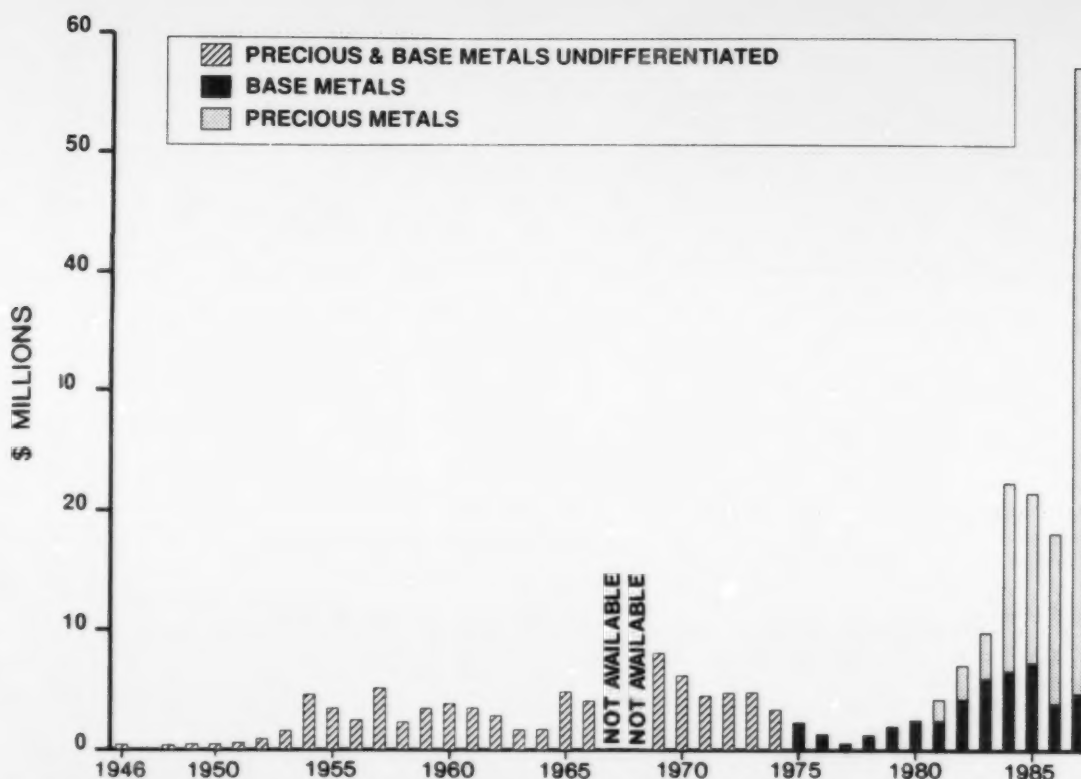


Figure 4 - Base metal and precious metals exploration expenditures in Saskatchewan, 1946-1987. Sources: 1946-1974 - calculated by D.A. Cranstone, using original Statistics Canada questionnaires received from companies, company reports to shareholders and Northern Miner Canadian Mines Handbooks; 1946-1966 'Prospecting' expenditures; 1968-1974 - 'General Exploration' and 'Minesite Exploration' including costs of 'Physical Work and Surveys' plus overhead expenses (land costs, administrative expenses in the field and exploration-related head office expenses); 1975-1983 - calculated by D.A. Cranstone using original Statistics Canada exploration questionnaires, which from 1975 on, included a question 'type of mineral sought'; 1984-1987 Federal-Provincial exploration survey (estimates of overhead expenses calculated by D.A. Cranstone using data in Statistics Canada catalogue 61-216).

in Saskatchewan during the 1930s and again from 1946 until the early 1960s, at which time exploration for gold almost ceased in the province. Gold exploration expenditures exceeded those for base metals in Saskatchewan during the 1930s and until at least the early 1950s. From the early 1960s until 1981, gold exploration was apparently insignificant. Therefore, Figure 4 essentially portrays base-metal exploration expenditures in Saskatchewan from about 1963 until 1975 and beyond.

Comparison of Saskatchewan Discovery Costs for Base Metals and Gold with Overall Canadian Discovery Costs

Figure 5 (Cranstone, 1988) shows Canadian mineral discovery success over the period 1946-82, in terms of the value of metals (excluding iron ore) discovered per dollar spent on exploration. The discovery values were calculated using January 1979 metal prices. These values include metal in all

mineral deposits discovered in Canada (both economic and uneconomic deposits), during that period. Although values include uranium, they still provide a reasonable scale against which to measure base-metal and gold discovery costs in Saskatchewan and compare them to discovery costs for Canada as a whole.

Figure 5 illustrates the outstanding Canadian discovery success, in terms of discovery costs, over the nine-year period 1948-56; the considerably lower, but relatively consistent discovery success per exploration dollar over the following 21 years, 1957-77; and, an apparent significant decline in discovery success per dollar spent on exploration in the 1978-82 period.

Although it has not been feasible to separate Saskatchewan exploration expenditures for base-metals from those for gold over the period 1946-74, it is pos-

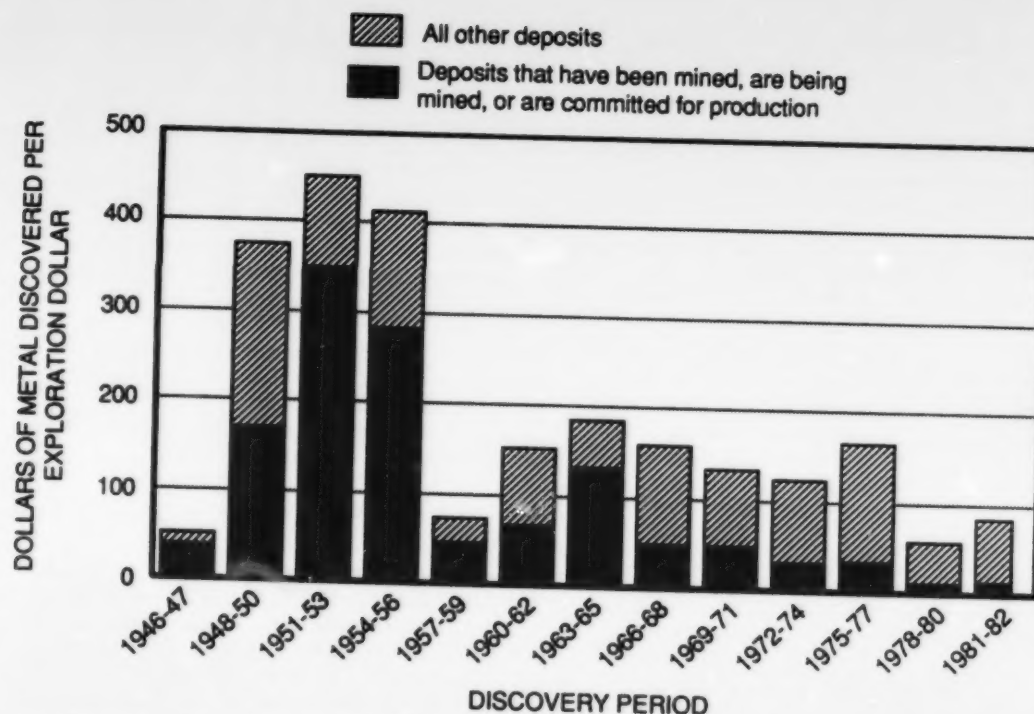


Figure 5 - Canadian mineral discoveries 1946-1987 metal value discovered per dollar spent on exploration per three year period. (Modified from Cranstone, 1988).

sible to measure joint exploration success for base metals plus gold (Table 5).

Table 5 - Base-metal and gold discovery costs in Saskatchewan 1946-87 inclusive.

- ° 'Value' of Base-Metals and Gold Discovered at January 1979 metal prices - \$86 billion
- ° Total Exploration Expenditures For Base Metals and Gold (in 1979 Dollars) - \$177 million
- ° Metal 'Value' Discovered per Exploration Dollar \$48 per dollar

Comparison of the \$48 of base metals and gold discovered in Saskatchewan per dollar spent on exploration with the \$190 of metals discovered in all of Canada per dollar of exploration over the entire 43-year period 1946-88 suggests that base-metal and gold exploration in Saskatchewan has not been especially favourable over the 43 years. This conclusion is further supported by the relatively small size of the few base-metal and gold mines that have been developed in the province since 1946. However, there appears to have been a notable improvement in discovery success in Saskatchewan since about 1982, because three significant base-metal deposits were found. All three are within 80 km of Flin Flon,

Manitoba. Discovery years, tonnages and grades of these three base-metal deposits are summarized in Table 6.

The Callinan deposit, immediately adjacent to the Flin Flon mine, is being mined from that mine. Although some mineralization was intersected by drilling on the Callinan property as early as the 1940s, the deposit consists of several mineralized lenses, and the mineable lenses of those were not discovered until 1984. Part of the deposit is in Manitoba, but as most of the mineable portion appears to be in Saskatchewan, in this analysis the entire deposit has been assigned to Saskatchewan.

All three deposits are open at depth, so that the tonnages in Table 6 don't represent all the metal they contain. In calculating discovery costs, it was assumed that the Bigstone Lake and McIlvenna Bay deposits contain twice as much metal as appears in the table. This multiplier of 2 is typical for Canadian copper and zinc deposits. It was assumed that the Callinan deposit, with several mineralized lenses, contains three times as much metal, because an unpublished analysis by the author has shown that 3.5 is a typical multiplier for multi-lens copper-zinc deposits of this sort in the Flin Flon-Snow Lake district of Manitoba and Saskatchewan.

Table 6 - Base-metal deposits discovered in Saskatchewan, 1980-88 (Information current as of November 1989).

- **1982 Bigstone Lake Deposit**
4,000,000 tons grading 1.87% Cu, 1.1% Zn, 0.29 ozs Ag/ton, 0.013 ozs Au/ton (includes 1,600,000 tons of 2.9% Cu and 340,000 tons of 11.2% Zn) (National Mineral Inventory, 1989)
- **1984 Callinan Mine**
2,600,000 tons grading 1.87 Cu, 3.7% Zn, 0.7 ozs Ag/ton, 0.055 ozs Au/ton (Hudson Bay Mining and Smelting Co., Limited, 1988 Annual Report)
- **1988 McIlvanna Bay (Hanson Lake) Deposit***
8,200,000 tons grading 1.1% Cu, 6.5% Zn, 1.0 ozs Ag/ton, 0.02 ozs Au/ton (Troymin Resources Ltd. Corporate Profile, October 1989)

*When the written version of this paper was prepared in July 1990, the reported tonnage and grade of the McIlvanna Bay deposit had increased to 11,700,000 tons averaging 1.0% Cu, 5.4% Zn, 0.7 ozs Ag/ton and 0.02 ozs Au/ton (Cameco - a Canadian Mining and Energy Corporation 1989 Annual Report). The deposit is still open at depth and in one direction along strike. This updated total has not been taken into account in the analysis of Saskatchewan discovery costs in this paper.

Over the 1980-1988 period (at January 1979 metal prices to be comparable to the data in Figure 5), \$81 of base metals were discovered in Saskatchewan per dollar spent on exploration (Table 7). This compares much more favourably with the overall Canadian mineral discovery cost, since 1957, of about \$125 per dollar spent on exploration. The \$81 of base metals discovered in Saskatchewan over the period 1980-88 actually exceeds the value of all metals discovered in Canada over the five year period 1978-82 portrayed in Figure 5.

Table 7 - Saskatchewan base-metal discovery costs, 1980-88 inclusive.

- 'Value' of metals discovered at January, 1979 metal prices = \$2,350,000,000
- Total base-metal exploration expenditures in 1979 dollars = \$29.0 million
- Metal value discovered per exploration dollar = \$81 per dollar

It is also encouraging that the three base-metal deposits discovered in Saskatchewan during the 1980s appear to have been of successively greater sizes and grades. While the discovery of larger and higher-grade deposits is not indicative of a future trend it does suggest that all the best deposits in Saskatchewan may not yet have been found, even near Flin Flon, where one might have been tempted to think that exploration possibilities could have been nearly exhausted after 75 years of exploration. As well, significant base-metal deposits have been found

in recent years in the adjacent region of Manitoba. The most notable of these is the Trout Lake copper-zinc deposit, an orebody that is proving to be of considerable size and which has been quite profitable to mine. The Namew Lake nickel-copper mine is another Manitoba ore discovery of the 1980s that lies in the Flin Flon-Snow Lake district. The recently discovered Chisel Lake North zinc orebody further to the east at Snow Lake, also looks promising. It seems reasonable to conclude that the Flin Flon-Snow Lake region of Manitoba and adjacent Saskatchewan still offers considerable promise for the discovery of new base-metal orebodies, almost 75 years after the original discoveries of the Flin Flon and Mandy orebodies and after the discovery of some 50 separate deposits of copper and/or zinc, more than half of which have been mined.

Gold Discovery Success in Saskatchewan During the 1980s

A number of promising (but not large) gold deposits have been discovered in the Precambrian Shield of Saskatchewan during the 1980s. At the same time, additional exploration work on deposits discovered in earlier decades has also considerably improved their economic potential. But how do discovery costs of the 1980s in Saskatchewan compare with those elsewhere in Canada? A major study of Canadian discovery success during the 1980s currently underway in EMR should answer that question. As with base-metals, it is only possible to compare the 'value', again at January 1979 prices, of Saskatchewan gold discoveries per dollar spent on exploration during the 1980s to the overall Canadian mineral discovery record of the period 1946-82. The highlights of the Saskatchewan gold discovery experience are shown in Table 8.

Table 8 - Saskatchewan gold discovery costs, 1980-87

- 'Value' of gold discovered in Saskatchewan at the January 1979 gold price of \$229/oz \$3,468 million
- Total Saskatchewan gold exploration expenditures 1980-87 (in 1979 dollars) \$64 million
- Gold 'value' discovered in Saskatchewan per dollar spent on exploration \$54 per dollar

Although the Saskatchewan gold discovery experience (\$54 of gold discovered per exploration dollar) does not compare especially favourably with the overall Canadian discovery experience of the post World War II period (\$190 of metal discovered per exploration dollar - see Figure 5), or for the period 1957-82 (\$125 of metal discovered per exploration dollar), it does compare more favourably with Canadian discovery costs for the five-year period 1978-82 (\$66 discovered per exploration dollar) and

probably with the Canadian discovery costs for the balance of the remainder of the 1980s. Since most of Saskatchewan's gold exploration during the 1980s took place in the second half of the decade, the information has not yet been obtained about all of the gold deposits and the amount of gold that will ultimately prove to have been discovered in the province during the 1980-88 period.

SUMMARY AND CONCLUSIONS

Highlights of Saskatchewan mineral exploration success include:

- ° The discovery of 99% of Canada's total known potash reserves and resources.
- ° The discovery of some 90 trillion tonnes of halite, which constitutes a major portion of Canada's known resources of salt.
- ° The discovery of 90% of Canada's reserves of sodium sulphate.
- ° The discovery of 10% of Canada's reserves of coal.
- ° The discovery of 50% of all the uranium in Canadian deposits, most of it in promising high-grade deposits.
- ° Low average uranium discovery costs over the period 1971-83 of \$1.70 (1988 dollars) per kilogram of uranium, compared with the Canadian average of \$15.11 per kilogram of uranium discovered for the same period.
- ° Average discovery costs for base-metals and for gold during the 1980s that are comparable to those in other parts of Canada.

- ° A notably improving trend in Saskatchewan discovery costs for base metals and for gold during the 1980s, relative to the previous 35 years.

With such a notable exploration and discovery record, Saskatchewan has been, and is likely to remain, an attractive Canadian target for mineral exploration.

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ACKNOWLEDGEMENTS

I have gratefully made use of exploration expenditure data painstakingly compiled some years ago by Yvonne van Ruskenveld and Robert Whillans from the original Statistics Canada questionnaires for the period 1946-75. Without their efforts much of the exploration analysis presented in this paper would not have been possible. Thanks are also owed to my colleague, André Lemieux for editorial assistance in making this paper more readable.

PATTERNS OF METAL ENRICHMENT IN VEGETATION IN RELATION TO GEOLOGY AND GOLD MINERALIZATION: STAR LAKE AREA, SASKATCHEWAN

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ABSTRACT

Biogeochemical surveys of differing scales have provided regional and detailed information on the chemistry of the substrate within a 150 km² area in the La Ronge gold belt. Outer bark of black spruce (*Picea mariana*) and twigs of shrub alder (*Alnus crispa*) were collected from approximately 600 sites and analyzed for 35 elements. Kriging of the data has been employed to display areas where there is enrichment of gold and associated elements.

A computer-generated model to predict areas favourable for gold mineralization revealed several areas considered worthy of closer examination. Further sampling of the same species plus Labrador tea (*Ledum groenlandicum*) has indicated a spatial relationship among gold, molybdenum and cesium in areas where mineralization is known, and in others where none has yet been discovered.

Labrador tea growing in a bog near the Jasper gold deposit indicates a strong Au, Co, W, Th and U association which may reflect the nature of the mineralizing fluids. All samples of Labrador tea within the 1 km² area surveyed around the Jasper deposit have above background enrichment in gold.

At 'Nameless' Lake gold enrichment in three vegetation types suggests the local presence of gold mineralization.

INTRODUCTION

Over the past fifty years, biogeochemical studies have firmly established that gold and other metals can accumulate in some plant species, and that each species has its own chemical characteristics. Literature reviews of the application of biogeochemistry to gold exploration have been compiled by Brooks (1982), Erdman and Olsen (1985), and Dunn (1989). The extensive and powerful root systems of plants absorb to varying degrees those elements encountered in the substrate, depending on the requirements and tolerances of a plant species. Chemical information obtained from the analysis of plants may be different from that of a soil: the roots integrate the geochemical signature of several cubic metres of various soil

horizons, the contained groundwaters, and locally the bedrock. Hence, biogeochemistry can be considered a holistic approach to geochemical exploration.

The relationship of metal accumulations to zones of mineralization is not always obvious. One complicating factor is that local physicochemical conditions may give rise to abnormal accumulations of metals in some plants. For example, in some environments large diffuse biogeochemical zones of metal enrichment occur; elsewhere a biogeochemical anomaly may be directly above its source, or displaced - either by groundwater movements, glacial dispersion, or both.

To further our understanding of the regional and local patterns of metal enrichments observed in common trees and shrubs of the forest-covered La Ronge belt, multi-element studies have been conducted. In addition to simple plots of the data, studies have been made of the spatial relationship of metal enrichment in the vegetation to bedrock geology, structure, and mineral occurrences. This has been achieved by making use of a geographic information system (GIS) to overlay several data sets. The system software used in this study is SPANS, manufactured by Tydac Corporation, Ottawa.

THE STUDY AREA - ITS GEOLOGICAL AND PHYSICAL ENVIRONMENT

The 150 km² study area is located in the Precambrian Shield 115 km northeast of La Ronge (Figure 1), in a region of forested, rolling hills. The dominant tree is black spruce (*Picea mariana*) interspersed with shrub alder (*Alnus crispa*), and Labrador tea (*Ledum groenlandicum*). The alder dominates recent burn areas, since it is a pioneer species which fixes nitrogen in the ground to provide the appropriate chemical environment for forest development. Jack pine (*Pinus banksiana*) and some white spruce (*Picea glauca*) occur with the black spruce in well-drained areas. Alder is generally absent from the scattered stands of trembling aspen (*Populus tremuloides*) and paper birch (*Betula papyrifera*). Boggy areas are common and the numerous lakes and streams constrained the orientation of the sampling traverses.

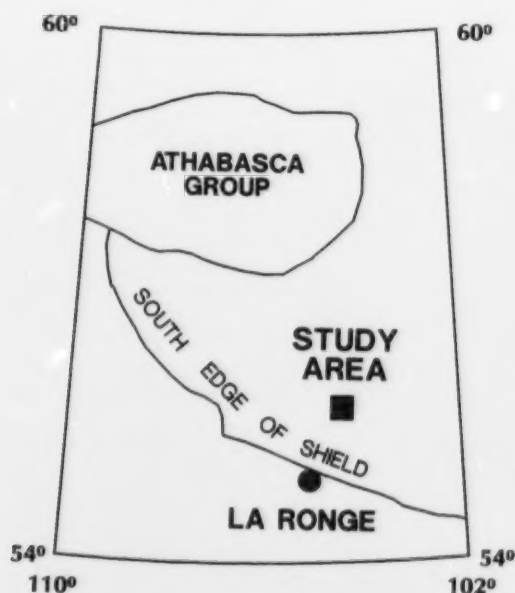


Figure 1 - Location of study area.

The survey area lies mostly within the La Ronge Domain. Bedrock comprises mainly mafic to intermediate metavolcanic and derived metasedimentary rocks that are intruded by felsic plutons, and one gabbroic pluton at Neyrinck Lake (Figure 2). Most of the felsic plutons have granitic centres which grade outward through granodiorite and monzonite to diorite at their margins. Shear zones are common and a major tectonic zone along McLennan Lake defines the southeastern limit of the La Ronge Domain. Detailed accounts of the geology of the area are given by Thomas (1984, 1985), Harper (1986), Lewry (1983, 1984), Poulsen *et al.* (1987), and Ames *et al.* (1987).

Within the limits of the regional biogeochemical survey there are several zones of gold mineralization, including the Star and Jolu (including the Rod Zone) gold mines (Figure 3). The gold is commonly associated with pyrite and pyrrhotite in quartz veins emplaced within shear zones cutting felsic plutons. Native gold is rare at some sites (Star Lake), but common at others (Jolu). Other associated minerals include molybdenite, cobaltite, sphalerite, galena, and rare tellurides (e.g. bismuth).

THE SURVEYS

Surveys were conducted on three occasions: a) an orientation phase in August, 1985; b) a reconnaissance phase in June, 1986; and c) a follow-up and 'in-fill' phase, which included areas not sampled previously, in June of 1988.

The three most common species, black spruce, shrub alder, and Labrador tea, provided the biogeochemical sample media. Spruce bark and alder twigs were obtained at most sample sites, and Labrador tea (twigs) was added for some local surveys.

Sampling procedures involved scraping loose scales of bark from the black spruce, and snipping about 50 cm lengths of twigs (approximately the last three years of growth) from the alders. Consistency in sampling is critical because of the variations in chemistry that occur in the bark profile and different twig ages. For example, gold and arsenic are more highly concentrated in the outer than the inner bark of most conifers (Dunn, 1988). Therefore, if inner bark is included with some samples, analytical data from such composite tissues cannot be compared with those of outer bark only. In the case of alder twigs, molybdenum concentrates in the new growth, whereas barium accumulates in old tissue. Consequently, if two years growth is collected at one site, and 10 years at the next, major differences in the content of some elements will be due to inconsistencies in sampling and not to mineralization.

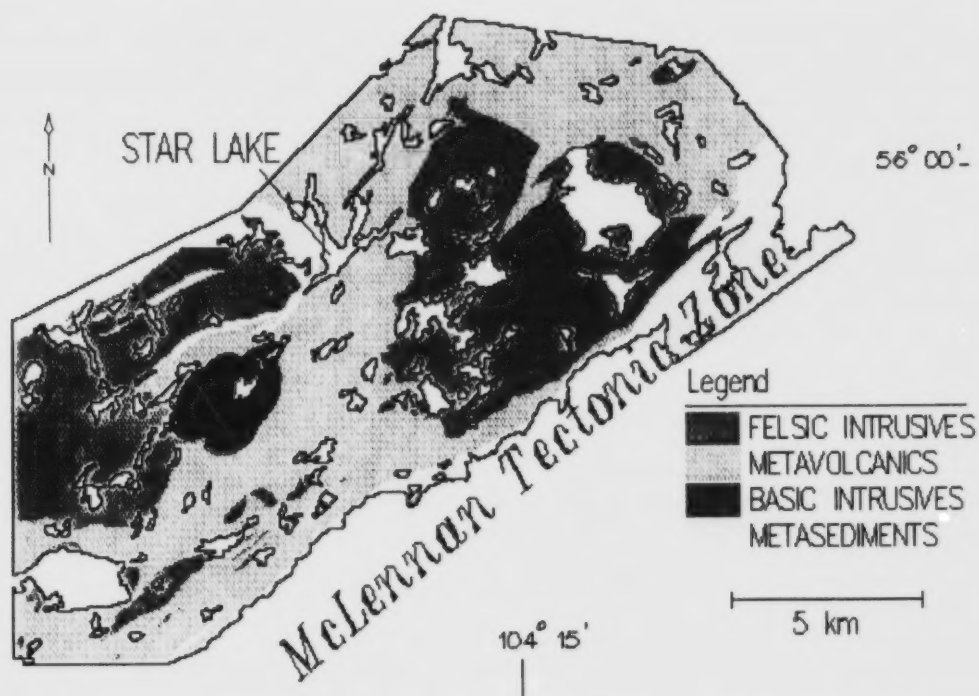


Figure 2 - Geology (simplified) of the Star Lake area. (After Thomas, 1984, 1985; Harper, 1985; Ames et al., 1987, Poulsen et al., 1987).

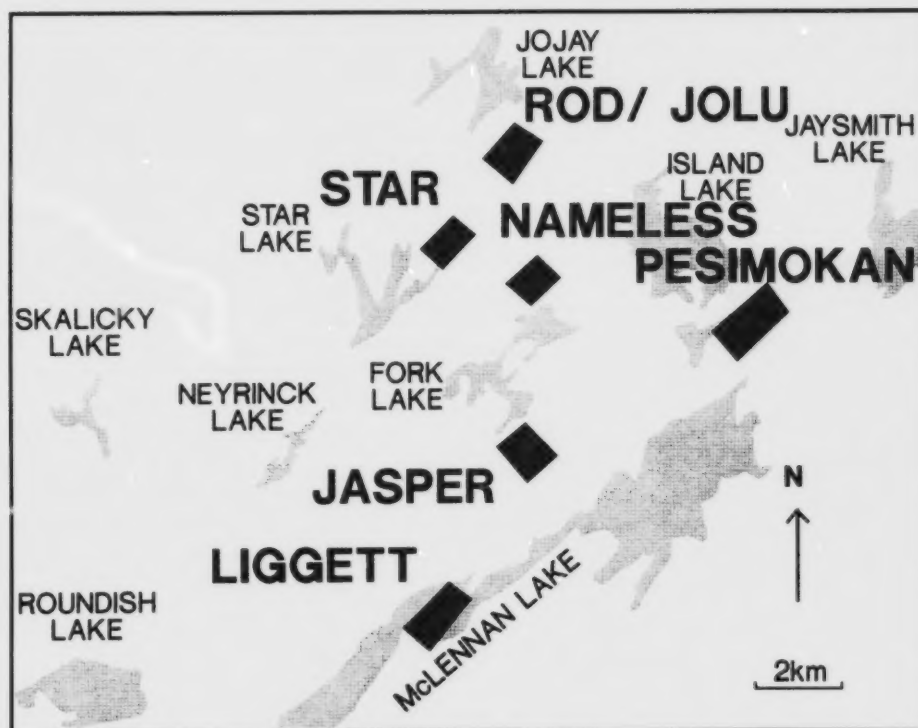


Figure 3 - Locations of mines and zones studied in detail.

Collecting Labrador tea involved snipping all the above ground parts, similar in appearance, of plants because it is impractical to determine and collect the same number of years of twig growth. Consequently, some variability of gold among Labrador tea samples may be attributable to the collection of different ages of twig growth. In alder twigs gold is fairly evenly distributed; therefore, by analogy most of the variation in gold content of Labrador tea is probably related to the gold content of the growth environment, and not to differences in the age of twigs.

Sample Preparation

Samples were air dried for several weeks, and the foliage separated from the twigs. The twigs were ashed in a kiln at 470°C overnight. Bark scales needed no preparation prior to ashing. Ash samples weighing between 0.5 and 1 g were accurately weighed and encapsulated for 35 element analysis by instrumental neutron activation (INAA). All data presented are concentrations in ash.

Orientation Phase - 1985

The first biogeochemical studies in this area were undertaken in 1985 prior to any mine development, and therefore prior to any possible contamination of the forest by mine workings. At that time the Jolu mine was just a prospect known as the Rod Zone, and the Star Lake mine consisted of proven reserves from diamond drilling. The Jasper gold mineralization had not yet been discovered.

Samples collected in the vicinity of the Star Lake gold mineralization yielded gold concentrations in alder twigs and spruce bark that are only slightly above background for the area. However, near the A-zone mineralization that subcropped beneath a bog, several plant species yielded anomalous gold concentrations, notably Labrador tea with over 100 ppb Au (Table 1). Background for all common plant species in the area is from < 5 to 20 ppb Au in ash. Although the spruce bark has only 16 ppb Au, subsequent studies showed this to be about five times the regional background.

At the time of the 1985 study, the quartz-hosted gold of the Rod Zone was projected to extend beneath a moist forested area, underlain by glacial deposits of uncertain thickness. Spruce bark samples were collected at a number of sites along this trend, and several proved to contain extremely high concentrations of gold (up to 690 ppb Au). A few samples of alder twigs from the same sites contain only a few times nor-

Table 1 - Gold content of ashed vegetation from 50 m south of gold mineralization that subcropped beneath a bog at Star Lake. Samples collected in August, 1985, prior to mine development.

	Au (ppb)
Labrador Tea (<i>Ledum groenlandicum</i>) - twig	110
Labrador Tea (<i>Ledum groenlandicum</i>) - leaf	36
River Alder (<i>Alnus rugosa</i>) - twig	42
River Alder (<i>Alnus rugosa</i>) - leaf	23
Dwarf Birch (<i>Betula glandulosa</i>) - twig	18
Dwarf Birch (<i>Betula glandulosa</i>) - leaf	22
Black Spruce (<i>Picea mariana</i>) - bark	16
Black Spruce (<i>Picea mariana</i>) - twig	7

mal background levels of gold (maximum of 34 ppb Au; background for this area is 10 ppb), but contain local enrichment of molybdenum (61 ppm; background < 2 ppm), and cobalt (28 ppm; background 5 ppm). Subsequently, Mahogany Minerals Inc. drilled in the vicinities of four of the bark anomalies, and intersected gold mineralization in each hole. A summary of the drill results, thickness of glacial overburden, and gold concentrations in the spruce bark is given in Table 2. This area is now the site of the Jolu mine.

Reconnaissance Survey - 1986

Given the encouraging results from the Rod Zone, a larger survey was undertaken the following year to collect samples from about 600 sites at 200 m intervals (Figure 4). Traverses were made throughout an area of 150 km² that extended from the MacLean Lake metasediments in the southeast, across the metavolcanics and plutons of the La Ronge Domain, and into the Crew Lake metasediments in the northwest. As noted earlier, the sampling grid was uneven because of the presence of many lakes, streams and bogs.

Table 2 - Relationship of anomalous concentrations of gold in ashed spruce bark to grades of underlying gold mineralization along the Rod Zone. Drill hole data courtesy of G. Burrill.

Gold (ppb) in Ashed Spruce Bark	Overburden Thickness	Drill Results
230	1 m	Near main trench.
120	1 m	Erratic mineralization: 1 m of 0.85 oz/ton (25 ppm) Au at depth of 50 m.
690	2.5 m	Subcropping mineralization - 0.11 oz (3 ppm) Au over 60 cm.
450	1 m	Subcropping mineralization - 0.3 - 0.7 oz/ton (10 - 22 ppm) Au over 4 m.
200	3 m	Mineralization, locally over 1 oz/ton (30 ppm), at shallow depth.

Background levels of Au in ashed spruce bark are, in this area, < 5 ppb

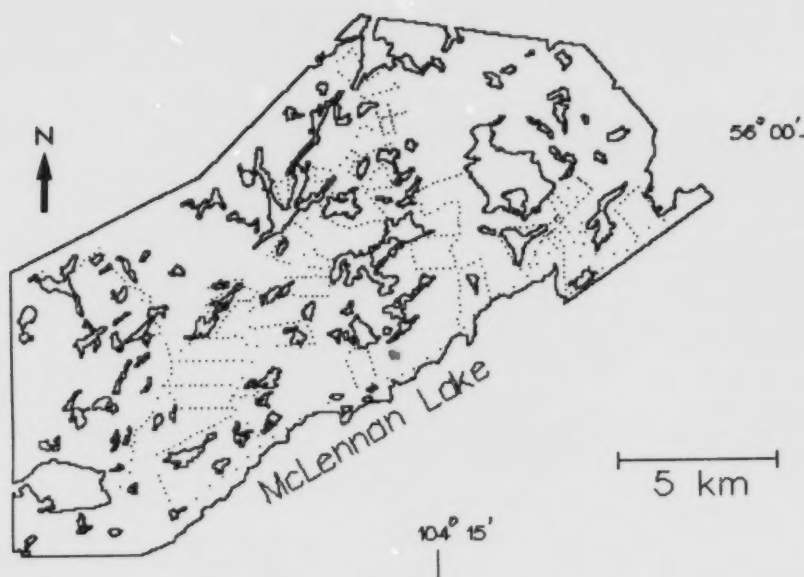


Figure 4 - Reconnaissance survey sample locations.

Data Interpolation

In view of the irregular spacing of sample locations, some care was necessary to ensure reliable interpolation of the data. This problem may occur in biogeochemical studies when a species is absent from part of the survey area, either as a result of environmental differences, or because of forest fires. Consequently, various interpolation schemes were investigated, and it was found that kriging (Clark, 1979) was suitable for plotting the data. Kriging also produces an estimate of the error associated with each interpolated value (i.e. the kriging variance). This value is useful for spatial modelling, since it allows the identification of unreliable estimates (George and Bonham-Carter, 1989).

Raw data values were reclassified into seven percentile classes, using thresholds ranging from the 50th to the 98th percentile, prior to interpolation by kriging. This transformation minimizes variance due to analytical noise, and enhances the differentiation of anomalous from background values. Kriging produces interpolated estimates along a regular grid of points distributed throughout the entire study area, including zones where no samples were taken. Since extrapolation into areas far from sample locations is probably meaningless, spatial limits were imposed on the extent of extrapolation from original sample points. This was implemented on the GIS system by restricting extrapolation to areas where the error associated with each kriged estimate was below a set threshold distance from the actual sample

point. This distance was 500 m for the reconnaissance study, and 100 m for the detailed studies.

Results

Once the data file is set up, it becomes a routine process to examine the distribution patterns of any element in any medium contained within the file. Only four of the elements analyzed (arsenic, molybdenum, cesium and gold) will be highlighted here.

Arsenic

The pattern derived from arsenic in spruce bark (Figure 5) shows that the highest concentrations occur in trees on the gabbroic rocks of the Neyrinck pluton (marked as 'basic intrusives' on Figure 2), and southward into the metavolcanics. Other isolated anomalies of lower magnitude occur farther to the east. In general, the arsenic concentrations are quite low throughout the study area. There is no indication that the distribution patterns might assist in locating gold mineralization, which is to be expected since a gold-arsenopyrite association is not known in this region.

Molybdenum

The map of molybdenum in alder twigs (Figure 6) indicates that the highest concentrations occur near the northeastern end of McLennan Lake. The raw data from this area shows that many samples have molybdenum concentrations that are considerably higher than the background of < 5 ppm, with a maximum concentration of 130 ppm Mo. The source of this enrichment has not yet been located in this area of poor exposure. It is noteworthy that at the Jolu mine gold mineralization is associated with molybdenite, hence there may be a similar association in this area.

Cesium

Cesium is a rare alkali metal which is normally present in ashed vegetation in concentrations of < 1 ppm Cs. It is, therefore, surprising that concentrations in the alder twigs are locally over 100 ppm Cs. Notable enrichment occurs in many samples from the granitic core of the Star Lake pluton, located just east of Star Lake (Figures 2 and 7). This 'granitic' association suggests that the Cs may be derived from the micas where it commonly substitutes for potas-

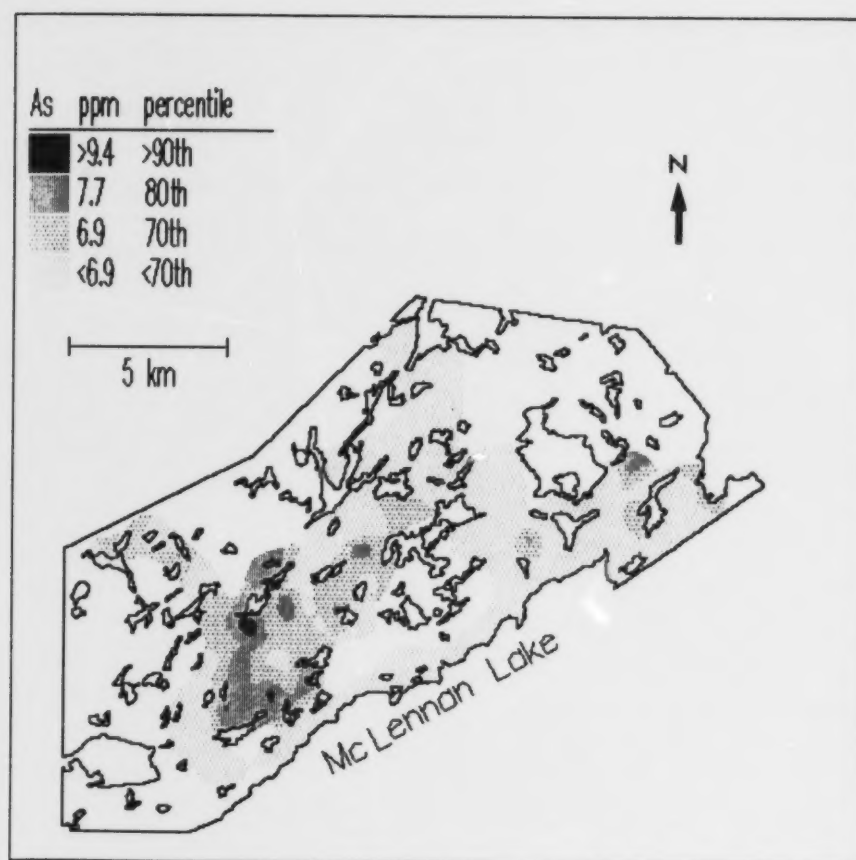


Figure 5 - Arsenic in outer bark of black spruce (kriged data).

sium. Locally there also seems to be a spatial relationship between cesium and gold enrichment in the vegetation. Only rarely have cesium minerals been identified in gold deposits: at Hemlo the extremely rare cesium-bearing mineral galkhaite has been reported (Harris, 1986). Cesium has also been found in steams emanating from several volcanic centres in the North Island of New Zealand. One of the authors (CED) collected vegetation growing close to the Champagne Pool in New Zealand, and found 140 ppm Cs in ashed tissue that also contains 1000 ppb Au, 86 ppm As, and 270 ppm Sb. Cesium enrichment was found at each of the six localities in New Zealand where vegetation was collected.

Gold

The plot of gold in alder twigs (Figure 8) shows that the highest concentrations occur in the east where no economic orebody is known. The spatial relationship of this zone of gold enrichment in alder to that of molybdenum is striking, suggesting a gold-molybdenum association in the substrate.

Weaker gold anomalies occur in zones of known mineralization, such as Star Lake and the Jolu Mine (Figure 3); however, the biogeochemical response in alder is subdued at these two localities because, prior to surface stripping, the subcropping mineralization occurred beneath bogs or moist woodland. In such environments gold uptake by alder is weak, whereas Labrador tea has the greatest gold concentrations. This emphasizes a significant point - that metal enrichments vary in different species according to the nature of the environment. Therefore, by considering the metal patterns of several species there is an improved chance of locating mineralized areas.

Relationship of Gold Anomalies to Geology and Structure

Figure 9 was produced using SPANS by superimposing plots of gold greater than the 90th percentile (for both alder twigs and spruce bark) on locations of known shear zones in felsic plutons. The McLennan Tectonic Zone was excluded from this basic computer model. These constraints were selected because of the proven occurrence of gold in sheared plutons in this area. The result is a prediction map indicating several areas considered favourable for gold mineralization, which provided a guide for follow-up work. Close examination of the raw data showed that some of these areas (e.g. west of Island Lake [Figure 3]) resulted from single samples that had gold concentrations close to the 90th percentile of one sample medium; therefore, they were not investigated in follow-up surveys. Others, however, had several samples with relatively high gold concentrations. One of these, 'Nameless' Lake, was selected for closer examination.

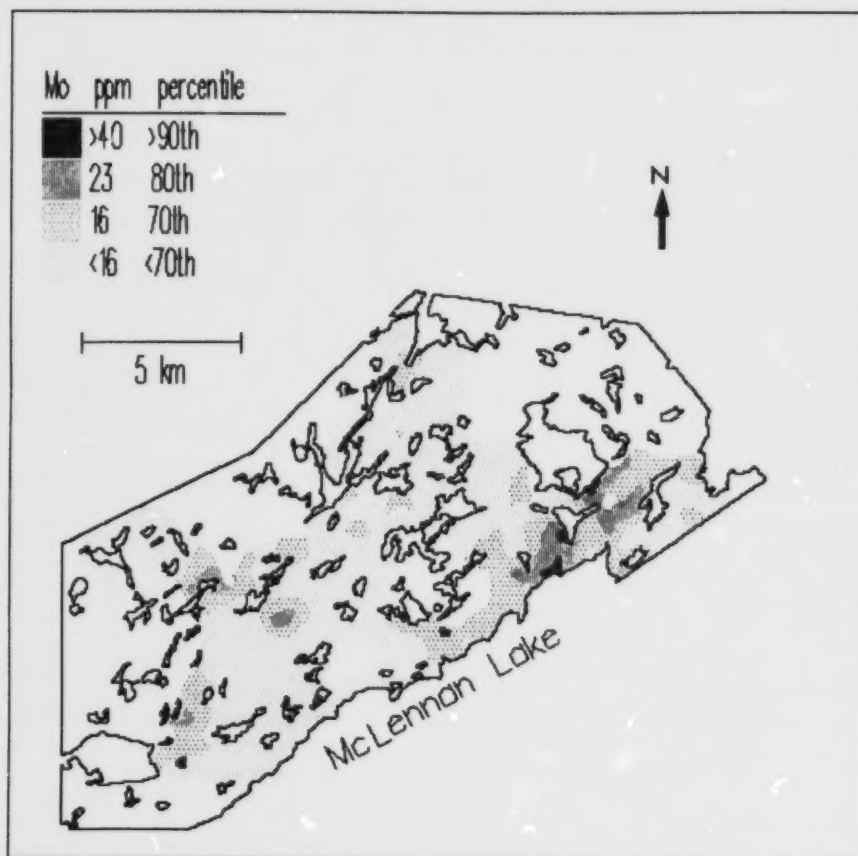


Figure 6 - Molybdenum in alder twigs (kriged data).

Detailed And Follow-up Surveys - June 1988

The 1988 survey involved revisiting several areas with gold enrichment in the vegetation to conduct more detailed sampling and surface investigations. Subsequent to the completion of the 1986 survey, the Jasper gold deposit was discovered in an area from which no samples had been taken, therefore investigations were extended into this area (Figure 3).

Liggett Bay

At Liggett Bay on the south shore of McLennan Lake (Figure 3), several samples from the 1986 survey yielded gold concentrations up to 50 ppb in spruce bark. No information was available on the bedrock or structure of this area so it did not appear on our constrained computer-generated model (Figure 9), but it did warrant a brief visit. A single grab sample of a coarse pegmatite outcrop contained 23 ppb Au (about 10 times the normal background level of gold in pegmatite). The analyses of several new samples of vegetation suggest that there is slight en-

richment of Au, As, and Zn in the area, but no indication of economic grades of mineralization.

Pesimokan Lake

To the east of Pesimokan Lake (Figure 3), resampling of an area which had previously yielded gold enrichment in many alder samples (Figure 8, and Dunn, 1986, 1987) reconfirmed that enrichment occurs close to the contact between the Island Lake Pluton and the McLennan Tectonic Zone. Local enrichments of As, Cs, Co, W, Se, Ni, and especially Mo are associated with gold in alders.

Figure 10 shows computer plots of kriged data for gold, molybdenum and cesium in alder samples obtained during the follow-up survey. (The

ragged outlines of the lakes are a function of the magnification of the digitized regional scale map). Maximum concentrations of the three elements are 80 ppb Au, 140 ppm Mo, and 43 ppm Cs. Although there is little overlap of anomalous areas, the spatial relationship of the elements indicates a possible metallogenic association related to a mineralizing event.

Rock samples were collected from this vicinity by a GSC geophysics crew the previous year, during an investigation of a pronounced linear magnetic anomaly. They were found to contain several percent magnetite intergrown with pyrite, pyrrhotite, chalcopyrite and molybdenite (B.W. Charbonneau, personal communication) and analyses indicate up to 3000 ppb Au.

From recent drilling in the area there appears to be a broad area of disseminated mineralization which is reflected in the vegetation as moderate concentrations of several metals. Approximately 2 km west of this anomalous zone, in an area of little outcrop,

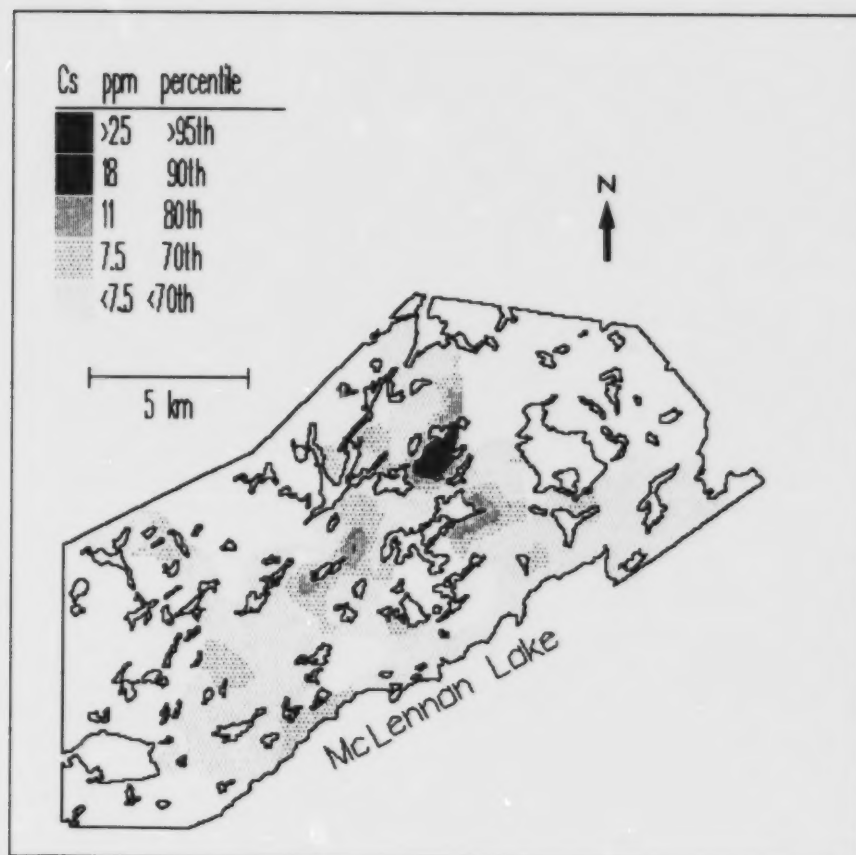


Figure 7 - Cesium in alder twigs (kriged data).

similar metal associations with slightly higher concentrations (350 ppm Mo, 110 ppb Au) occur in the alder, suggesting an extension of this mineralized zone (i.e. the main area of gold enrichment indicated in Figure 8).

Jasper Pond

Soon after the completion of the 1986 survey, gold mineralization was discovered by the Saskatchewan Mining Development Corporation (now Cameco) near Jasper Pond (Figure 3), in an area not covered by the survey. Here the bedrock consists of felsic to intermediate rocks of the Island Lake Pluton, intruded by mafic dykes, and disrupted by northeast-trending shear zones. Labrador tea samples collected by Cameco from close to the zone of gold mineralization soon after its discovery were found to be highly enriched in gold (up to 700 ppb Au) (V. Sopuck, personal communication).

nature of the mineralizing fluids from simple low-cost analyses of a few vegetation samples.

Plots of the kriged gold data from Labrador tea and spruce bark (Figure 11) both indicate the strong enrichment of gold in the southwest corner of the map. The Labrador tea map (Figure 11a) indicates a

Table 3 - Element concentrations in ashed twigs of Labrador tea from 9 sites in a bog adjacent to the north side of the discovery outcrop of gold mineralization at Jasper Pond.

	Range	$\bar{X}$	Background	Concentration Factor
Au (ppb)	38 - 289	129	20	6
As (ppm)	2 - 4	3	2	1.5
Co (ppm)	5 - 65	25	5	5
Cr (ppm)	12 - 37	25	10	2.5
Th (ppm)	1 - 3.6	1.8	.2	9
U (ppm)	<.1 - 3.3	1.4	<.1	>15
W (ppm)	<1 - 22	7.3	<1	>7

As part of the 1988 in-fill program, samples of spruce bark, alder twigs and Labrador tea were collected at approximately 100 sites within a 1.5 x 1 km area (Figure 11). High levels of gold (up to 779 ppb) in Labrador tea from the bog immediately north of the discovery outcrop confirmed Cameco's observations. Multi-element INAA provided new information on the chemical environment, and demonstrated that there are interesting enrichments of other elements in the Labrador tea. Table 3 shows the range of concentrations for several elements that are enriched relative to common background levels. Of note are the high concentration factors for Au, Co, Th, U and W. This association provides a good indication of the chemical

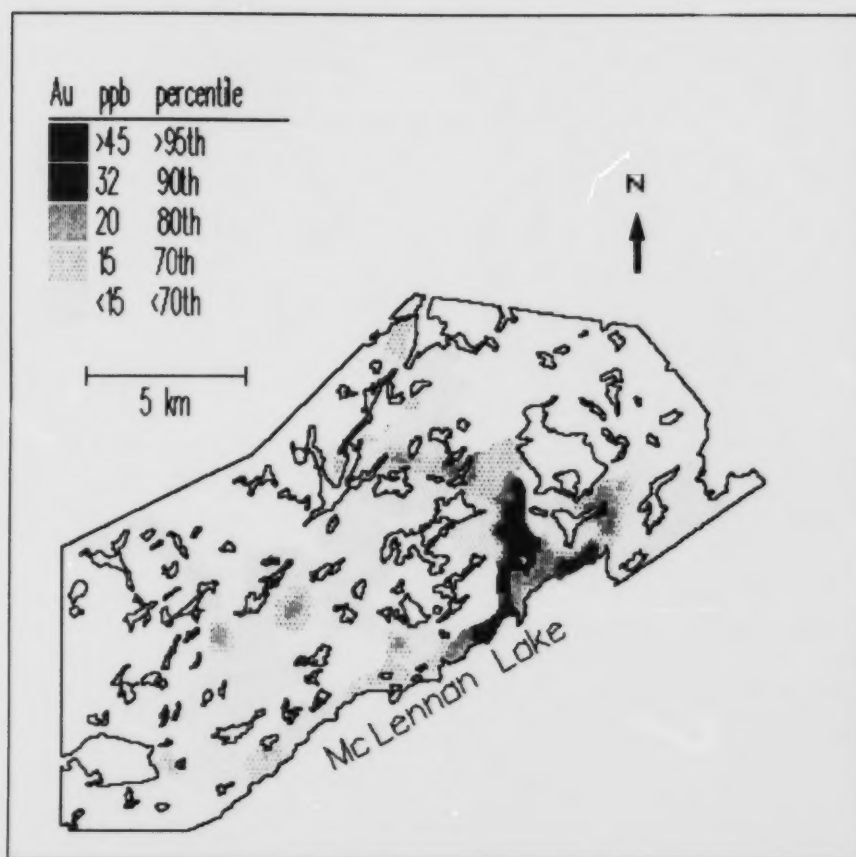


Figure 8 - Gold in alder twigs (kriged data).

second zone of gold enrichment in a boggy area about 500 m to the northwest, trending (along a shear zone) toward Broeder Lake. This zone is not apparent on the spruce bark map (Figure 11b), presumably because of the lack of sensitivity of spruce bark to the presence of gold in wet areas. The bark map does, however, indicate a second area of relative gold enrichment northeast of Jasper Pond where drier conditions prevail.

The multi-element data base for the three species obtained from this area provides additional information on the chemical environment. Along the shear zone north of Jasper Pond, delineated by gold in Labrador tea, alder twigs yield strong enrichments of Cs, Rb, Sr and Ni (with local enrichment of Au, Mo, and Co). The spruce bark at these sites reveals a Au, As, and Cr association. The nickel probably originates from the mafic dykes that are characteristic of the Star Lake pluton. The frequent association of gold, cesium and molybdenum in alder is again evident.

The entire Jasper survey area has gold enrichment in Labrador tea covering at least 1 km², providing a broad target for a reconnaissance style biogeochemical survey.

'Nameless' Lake

The 'Nameless' Lake area (Figure 3) was selected for study because it was predicted by the computer analysis model of the 1986 data as being favourable for gold mineralization (Figure 9). No samples were collected from the north side of the lake in the original survey. The bedrock here is granodiorite and monzonite of the Star Lake Pluton, intercalated with lesser amounts of mafic igneous rocks (Figure 12a). There is a wedge of felsic tuff adjacent to 'Nameless' Lake and a mylonitic zone beneath 'Pointy' Lake.

The three types of vegetation collected all contain anomalous levels of gold. Labrador tea (Figure 12b) contains up to 460 ppb Au, with the average gold concentration being appreciably higher than the average from the Jasper bog. Except for a weak enrichment of As (4 ppm) and Th (1 ppm), the other elements have close to background concentrations.

Gold and arsenic are enriched in the spruce bark (Figure 12c), with concentrations up to 60 ppb Au and 14 ppm As. Alder shows the same pattern for gold with up to 93 ppb Au at the northern sites (Figure 12d), but arsenic concentrations are only a few ppm above background, because alder establishes a barrier to arsenic uptake. Although cesium is not enriched in the immediate vicinity, there is strong cesium enrichment a short distance to the north (Figure 7).

Figure 12e summarizes the data by ranking the sites according to the gold concentrations in the three plant species. Sites in the first rank are those where

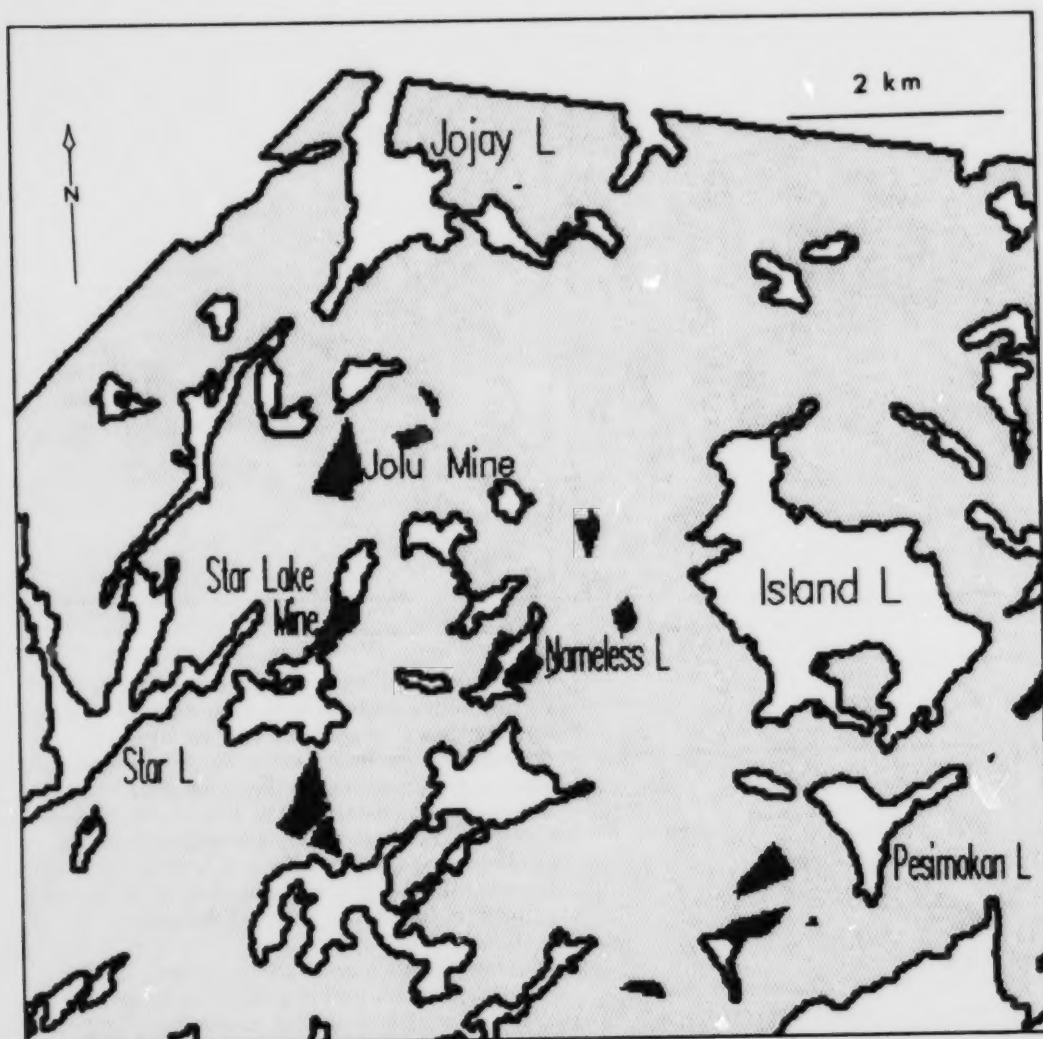


Figure 9 - Prediction map of zones favourable for gold exploration (black areas).

two sample media have gold concentrations that fall in the highest category (Figures 12b, c, and d), and the remaining vegetation type falls in the second category; rank '2' sites are those where all sample media have gold concentrations in the second category, or one medium in the top category and two in the second; and rank '3' sites have only two sample media in the top two categories. The highest concentrations occur in the northerly sites where high concentrations of gold also occur in heavy mineral concentrates (HMC) derived from the till. The range in HMC is from 30 to 4790 ppb, with gold grain counts from zero to 35 grains per bulk till sample (V. Sopuck, personal communication).

Of six holes drilled by Cameco beneath 'Pointy' Lake, four penetrated the mylonite, but only one in-

tersected gold mineralization. The biotite-rich mylonite contains minor pyrite and a 10 cm-thick quartz vein with massive pyrite, 3-5% galena and minor sphalerite. A core sample from this zone contains over 2000 ppb Au and 42 ppm Ag. A small mylonitic zone in the southwestern part of the study area also yielded 2000 ppb Au.

There is, therefore, tangible evidence that gold is present in the bedrock, but the weight of geochemical evidence is such that either there is more significant gold mineralization in the area yet to be discovered, or there are peculiar unexplained environmental conditions which have given rise to the biogeochemical gold anomalies. The former seems more likely since there is no known process that can give rise to such high levels of gold in vegetation in

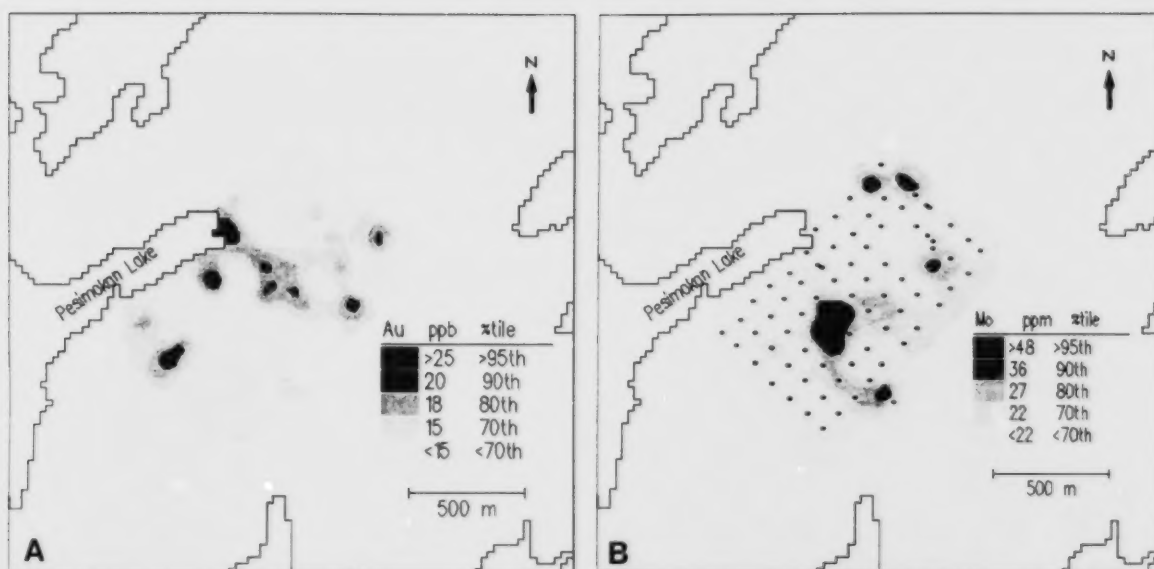
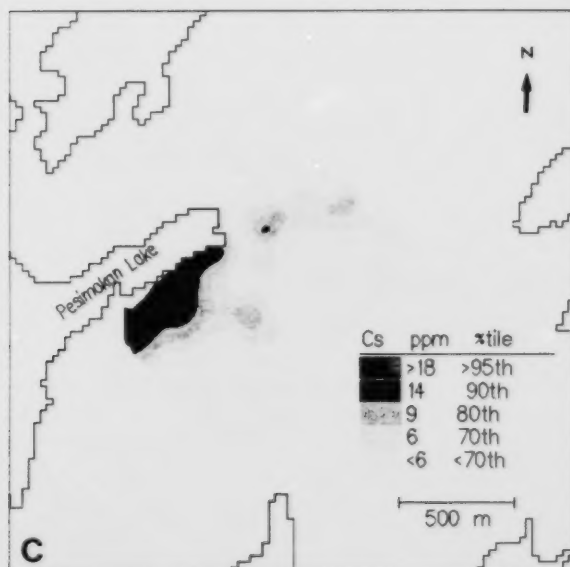


Figure 10 - Pesimokan Lake: a) Au, b) Mo And c) Cs in alder twigs



the absence of appreciable gold enrichment in the substrate.

CONCLUSIONS

The evidence presented suggests that multi-element reconnaissance style biogeochemical studies can assist in identifying areas of metal enrichment in the substrate that may be of economic interest. Computer modelling of the data, using a GIS system, can assist in the interpretation of the data and in providing focus for more detailed investigations.

Gold mineralization can be located directly by drilling high order biogeochemical anomalies, such as the high enrichment of gold in spruce bark from trees in the vicinity of the Rod Zone. Prior to drilling, however, careful consideration should be given to as many geological parameters as possible: in the case of the Rod Zone, geological mapping indicated that a gold-bearing quartz zone probably extended beneath tills, and the biogeochemical survey helped to focus on gold-bearing parts of that zone.

Data interpretation is not always a simple task, because slight enrichment of gold in vegetation may be related to weak near-surface enrichment of gold in the bedrock, or to deep-seated mineralization of more significance. Furthermore, each species has its own chemical characteristics and ability to concentrate elements. One species, such as black spruce, may give a good response to gold in the substrate in one environment (e.g. woodland), but a weak response in another (e.g. bogs). By adopting a multi-element, multi-species approach a comprehensive picture of the nature of underlying mineralization can be obtained.

By analogy with patterns of metal enrichment observed in plants near known gold mineralization at the Jasper deposit, it seems probable that other gold deposits are present in the study area, particularly to the northwest of 'Nameless' Lake.

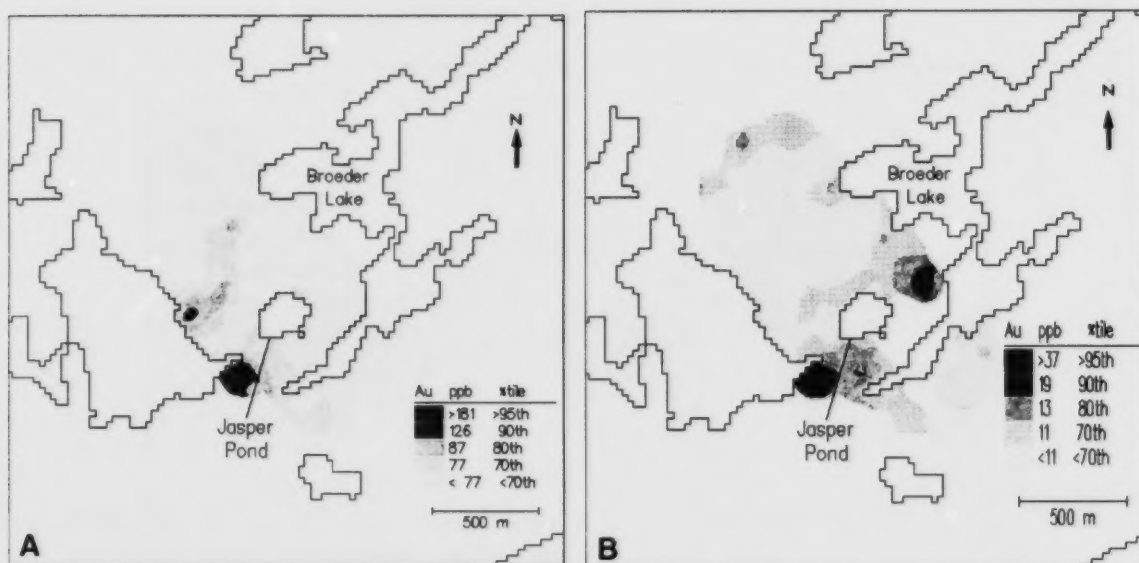


Figure 11 - Au in a) Labrador tea and b) spruce bark (kriged data).

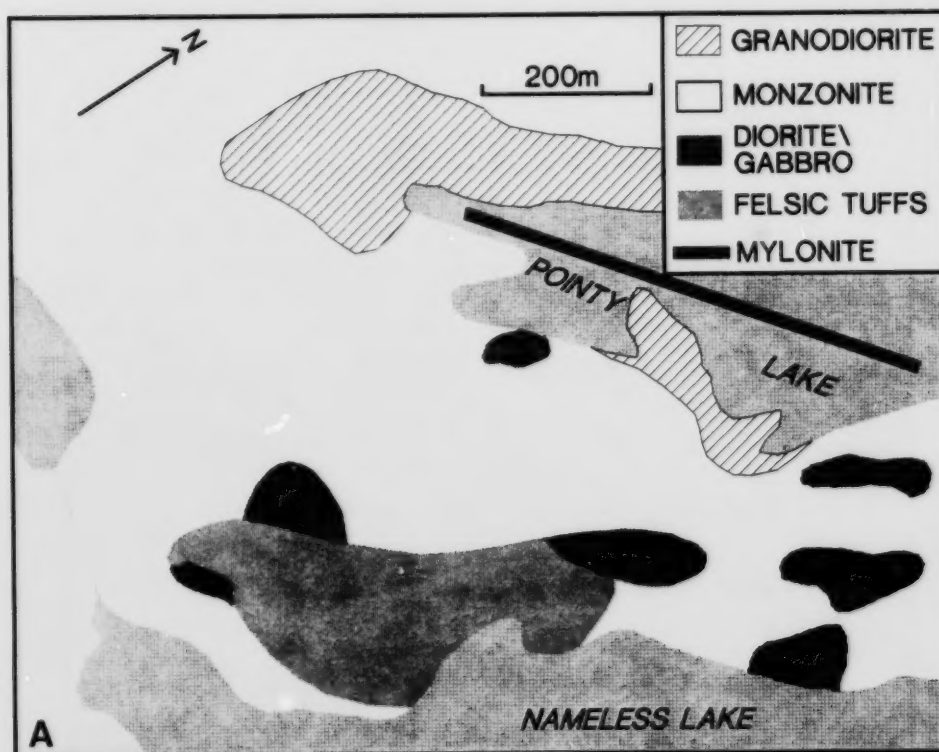


Figure 12a - 'Nameless Lake' geology (modified from map compiled by D. Chan - personal communication from Cameco).

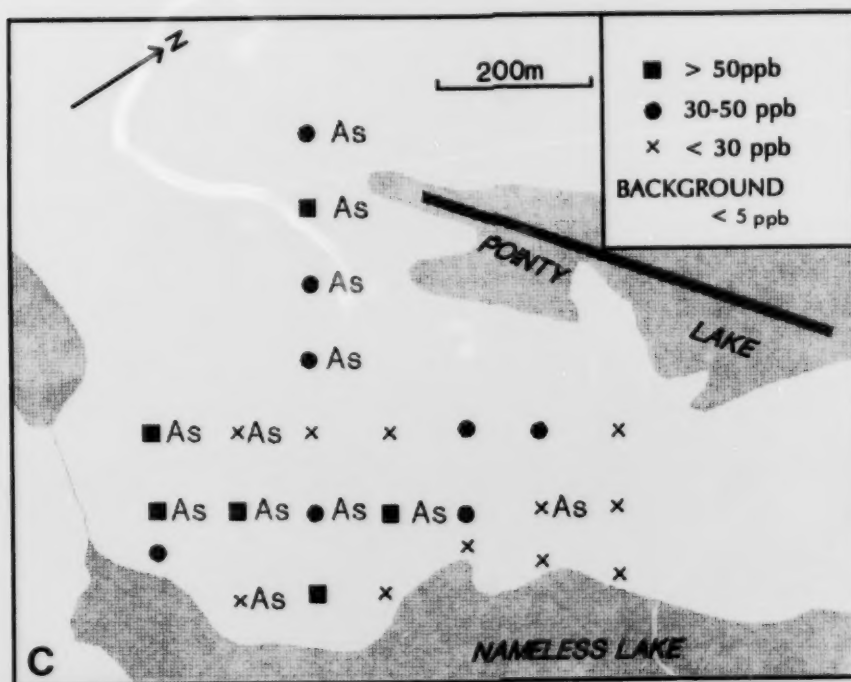
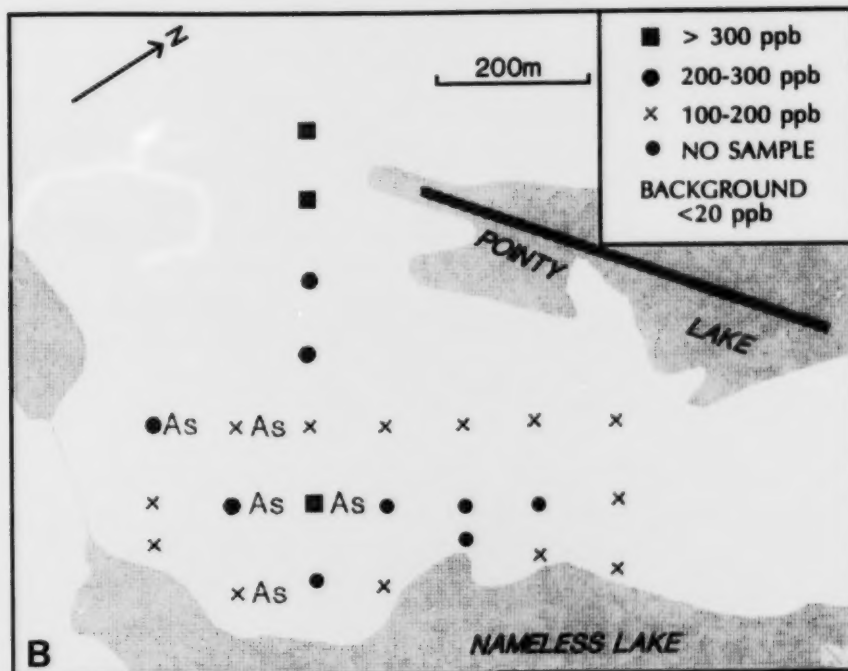


Figure 12 - 'Nameless Lake': b) gold in Labrador tea twigs, c) gold in black spruce outer bark.

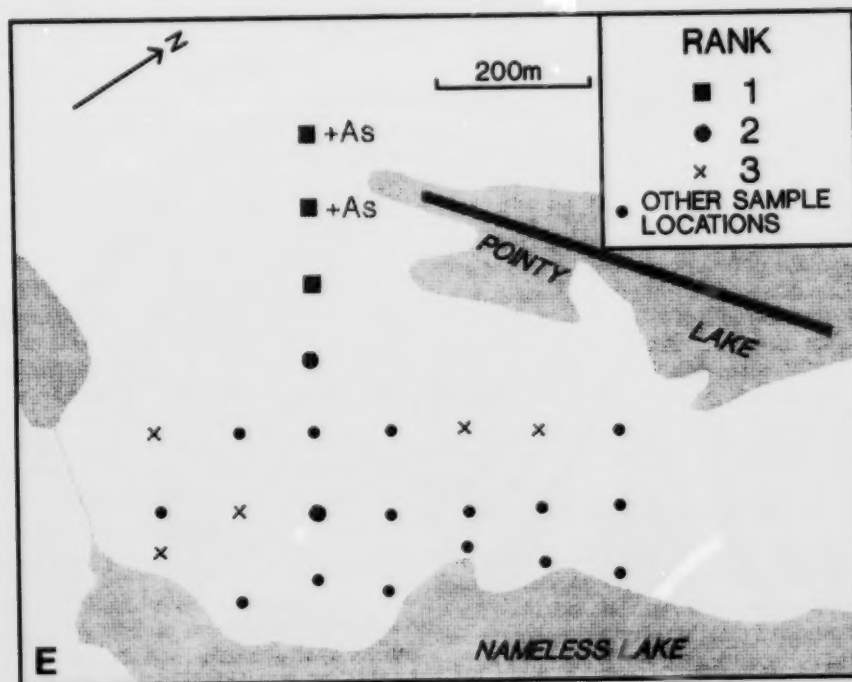
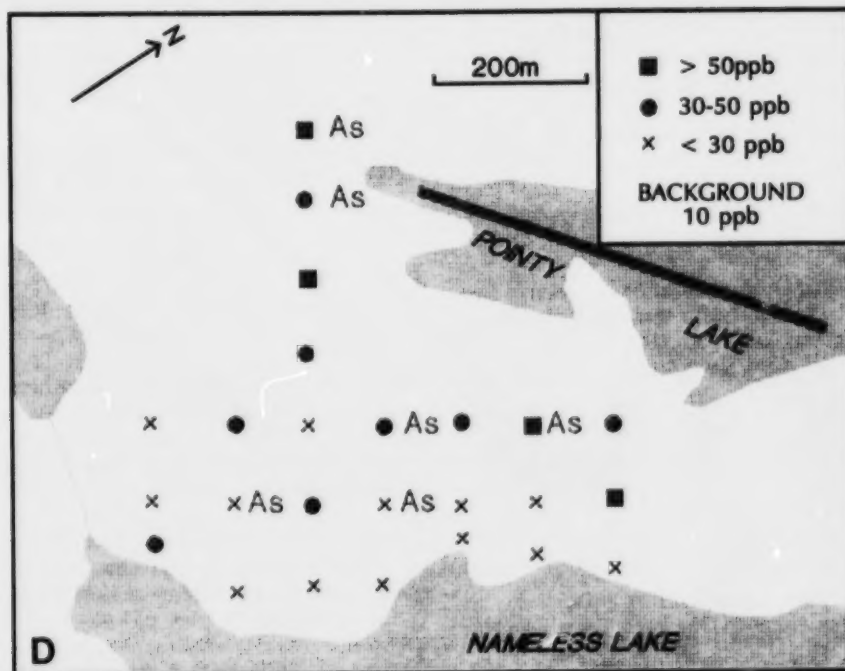


Figure 12 - 'Nameless' Lake: d) gold in alder twigs, e) gold in the three vegetation sample media, ranked in order of decreasing gold concentrations and anomaly coincidence.

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ACKNOWLEDGEMENTS

We thank G. Burrill (formerly of Mahogany Minerals Inc.); R. Kusmirski, V. Sopuck, and D. Chan (Cameco); and B. Charbonneau (GSC) for supplying us with information that has assisted in the interpretation of this study. We gratefully acknowledge the permission granted by Mahogany Minerals Inc. and Cameco Ltd. to publish drill hole, geological, and geochemical information.

MASS BALANCE CORRECTIONS APPLIED TO LITHOGEOCHEMICAL DATA IN MINERAL EXPLORATION

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ABSTRACT

Rock alteration is typically associated with mineralization, thus altered rocks comprise an important exploration target. During alteration, material may be introduced into or removed from the protolith; there is, however, no basis for assuming that the gains and losses will balance and, in fact, many recent studies have shown that mass changes of significant magnitude are common, especially when the alteration takes place under near-surface conditions.

Examples of active geothermal/hydrothermal phenomena from New Zealand and the Philippines and ancient 'granitization' effects from the Goldfields area of northern Saskatchewan have been developed to illustrate the relevance of this approach.

The use of 'net compositions' (i.e. analyses corrected for gains and losses of mass during alteration) adds precision to initially noisy data, can define alteration limits and zonal boundaries more accurately than is possible with raw data and introduces a new variable to the tools of the alteration geochemist, that of the mass change factor. The latter may be a valuable adjunct when reconstructing ancient alteration/mineralization patterns.

INTRODUCTION

Changes of rock mass during hydrothermal and other types of alteration can frequently be implied from observations at active centres of alteration or on rocks exhibiting ancient alteration effects. Sinter terraces at recent geothermal sites imply the leaching of SiO_2 and other constituents of the sinter from the rocks beneath in the geothermal system. The solutes in the expelled geothermal fluids include many other elements which were also leached from within the geothermal flow system. The clouds of precipitates ejected from submarine 'smokers' are another manifestation of this phenomenon. Similarly, veins of a dilatant character in hydrothermal breccias imply an addition of the vein material on at least a local scale indicating, thereby, a local increase of rock mass.

In most examples of altered rocks, however, mass changes are not visibly evident, or, if they are, the magnitudes of the mass changes may appear to be indecipherable. Nevertheless, a rapidly growing number of studies is indicating that mass changes during alteration are the rule rather than the exception espe-

cially under near-surface conditions and, furthermore, the magnitudes of these changes may be substantial in both negative and positive senses.

The use of 'raw' lithogeochemical data in comparative contexts involves the implicit assumption that no change in mass has occurred. For some purposes, the errors introduced by this assumption may be permissible as, for example, in the first-order regional search for geochemically anomalous major units or for large exposed alteration halos. When, however, the search becomes more focused or where subtle alteration effects are sought, large discrepancies in the lithogeochemical data are unacceptable and it is necessary to remove as much of this 'constant mass noise' from the data-set as possible.

The problem of integrating mass change systematics into the routine use of lithogeochemical data has always been that the magnitude of the mass change has been unquantifiable by objective means. In the face of this problem it has been customary to resort to subjective constraints, e.g. (1) most commonly, to ignore any mass changes altogether, (2) to assume that alteration has been isovolumetric while making cor-

rections for density changes, (3) to assume some element such as Ti, Al, Zr or one or more of the rare earths has been immobile during the alteration. The latter procedure permits volume changes to be calculated subject to the validity of the assumption which is generally unsupported by direct evidence.

The other common procedure designed to avoid the problem is to limit one's use of geochemical data to dimensionless ratios; ratios are valid applications of data but in restricting use to ratios the information inherent in the absolute levels of elements is totally lost.

A solution to this problem resides in the Gresens General Metasomatic Equation (Gresens, 1967). Groups of elements that are neither gained nor lost during alteration, the so-called *immobile* elements, characterize most types of alteration conditions. These immobile elements can be identified with a high degree of objectivity and confidence by their non-dispersed (i.e. clustering) distributions in lists of *zero change volume factors*, parameters derived directly from the Gresens equation. This information permits the volume change ratio of each altered sample to be calculated with respect to a reference protolith (parent rock), whereupon the product of the volume change and density change factors, the latter from measured values, gives the mass change ratios needed to compute actual gains and losses.

Objectives and Scope

The intention of this contribution to the Symposium on Modern Exploration Techniques can be summarized as follows:

1. to review the concepts of mass balance calculations with respect to altered rocks;
2. to illustrate the magnitudes of volume, density and mass changes with respect to:
 - a) alteration in modern geothermal/epithermal settings of New Zealand and the Philippines;
 - b) 'granitization' effects in the Frontier granite of the Goldfields area, Lake Athabasca, Saskatchewan;
3. to illustrate comparisons between mass balance corrected data and 'raw' data;
4. to suggest applications of the mass balance correction technique in the field of mineral exploration.

The examples presented in this paper are chosen solely to illustrate the application of these computational approaches. The validity of any interpretations based on these data will be or have been argued in other publications.

METHODOLOGY

Outline of Gresens Equation and Determination of Zero Change Volume Factors

The general equation expressing the difference in composition between a fresh rock and one to which it has been altered was formulated by Gresens (1967). The relationship is simple and can be derived intuitively.

The difference in composition, Δx , between any unaltered rock or parent, α , and its altered equivalent, β , can be expressed for any element, η by the arithmetic difference between the concentrations of the element, x^α_η and x^β_η , in the two analyses as follows:

$$\Delta x_\eta = x^\beta_\eta - x^\alpha_\eta \quad (1)$$

However, the values so obtained only express the gain or loss of each element if the masses on both sides of the equation are equal, e.g. if 100 g of the parent rock has been converted during alteration into exactly 100 g of the altered rocks. Since there is no *ad hoc* reason why this restriction should apply in nature, it is necessary to consider that a change of mass may have occurred during the process, whereupon the mass-balance equation becomes:

$$\Delta x_\eta = (M^\beta \times x^\beta_\eta) - (M^\alpha \times x^\alpha_\eta) \quad (2)$$

where M^α and M^β represent the masses of the parent and altered rocks respectively, i.e. the mass *before* and *after* alteration. On dividing the equation through by M^α and clearing the fraction on the left side we get:

$$\Delta x_\eta = M^\alpha \left(\frac{M^\beta}{M^\alpha} \times x^\beta_\eta - x^\alpha_\eta \right) \quad (3)$$

Since the raw data are expressed in wt.% and ppm units, it is convenient to select the arbitrary initial mass unit, M^α , as 100 g or 10^6 g, whereupon the initial M^α on the right side of the equation cancels out and the equation becomes:

$$\Delta x_\eta = \frac{M^\beta}{M^\alpha} \times x^\beta_\eta - x^\alpha_\eta \quad (4)$$

with x^α_η and x^β_η represented by their wt.% or ppm values now expressed in absolute terms, i.e. grams.

It is convenient and equivalent to replace the mass terms, M^α and M^β , by the product of the rock density, ρ , and volume, v , and are thereby offered in the Gresens equation below:

$$\Delta\chi_{\eta} = \left(\frac{\nu^{\beta} \times \rho^{\beta}}{\nu^{\alpha} \times \rho^{\alpha}} \times \chi_{\eta}^{\beta} \right) - \chi_{\eta}^{\alpha} \quad (5)$$

This equation contains two unknowns, $\Delta\chi_{\eta}$, and ν^{β}/ν^{α} , the volume change factor, which can be replaced for convenience by the variable name FV. For $\Delta\chi_{\eta}$ to be solved it is therefore necessary to determine the value of FV for every altered rock. (This is the reef on which all previous attempts at mass balance calculations have foundered!). Gresens (1967) noted that one solution is to measure the volume change by some physical parameter such as the amount of offset present in structures on either side of dilational veins, but this approach is nearly always impossible. A second approach, he noted, is to assume the immobile behaviour of some single element. In this case the $\Delta\chi_{\eta}$ for the assumed immobile element becomes zero and the consequent FV for this assumption is calculated by the relationship –

$$FV_{\eta}^0 = \frac{\rho^{\alpha} \times \chi_{\eta}^{\alpha}}{\rho^{\beta} \times \chi_{\eta}^{\beta}} \quad (6)$$

where FV_{η}^0 is the volume change factor for the case where there is zero change in the element η , i.e. η is immobile. It must be accepted, however, that assumptions of immobile behaviour without independent verification lack credibility. Gresens' third and most acceptable approach is to postulate that in most cases of alteration there will be a group of elements that will possess effective immobility. Furthermore, this property can be recognized inasmuch as all such elements will have closely similar FV^0 values for each parent $\rightarrow$ altered rock comparison. If the FV^0 values for all elements in the analyses are computed for all parent $\rightarrow$ altered rock comparisons, immobile elements will be recognizable by the tendency of their respective FV^0 values to cluster together within each list. The best estimate for the actual volume change factor for each altered rock is therefore the mean of the FV^0 values for all the elements that exhibit these immobile characteristics.

An example of this approach is given in Table 1. Partial analyses of a parent and its altered derivative are listed in columns 1 and 2. Column 3 contains a list of the FV^0 values for each element calculated using equation 5, above. In this list there is a cluster of 4 FV^0 values with an average of 1.10, i.e. TiO_2 - 1.10, Al_2O_3 - 1.11, V - 1.12, and Zr - 1.08. If other parent $\rightarrow$ altered rock pairs also had the FV^0 values of these four elements forming clusters, though not necessarily nor likely at the same value, these associations could be accepted as evidence of mutual immobile behaviour and not the result of coincidence. In each case, the average of their FV^0 values would give the volume change ratio for that parent $\rightarrow$ altered rock

pair. In the example given, the best estimate of the volume increase during alteration was 10%. The density change ratio in this instance is 1.07 and the mass change ratio is therefore 1.18, i.e. an 18% increase.

Identification of Immobile Elements

In practise, it is common to find when investigating the identity of immobile elements that a greater number of elements satisfy the criterion for immobility when alteration intensities are low than when they are high. It will also be apparent that immobile element lists may be quite different for alteration of a rock by different types of fluids or under notably different P/T conditions. Furthermore, elements with a low pre-alteration variance in the parent rocks will be more readily identified as immobile by the criterion proposed above than elements with high primary variances. FV^0 values of the latter elements will also possess high variances and may fall outside the apparent limits of the cluster used to identify the immobile element group. High variance elements will, however, be identified by their lack of systematic change when plotted on alteration variation diagrams.

Compositional Changes and 'Net Compositions'

Elemental fluxes during alteration are conventionally displayed in the form of 'gain/loss' data, the form produced by the Gresens equation. The 'gains' and 'losses' are relative to the reference or parent rock composition. An alternative way of expressing the alteration is in the form of the altered rock's *net composition*. This expression is obtained by adding the computed gain or loss to the respective reference (least altered) analysis, i.e. by the relationship $NC_{\eta} = \chi_{\eta}^{\alpha} + \Delta\chi_{\eta}$. The net composition of an altered rock resembles the *raw* analysis but expresses

Table 1 - A hypothetical example of calculating mass balance-corrected gains and losses using Gresens equation. See text for explanation. Units for SiO_2 - S, wt.%; V - Sr, ppm.

	Parent	Altered	FV^0	$\Delta\chi_{\eta}$ for $FV=1.10$	NC_{η} for $FV=1.10$
Density	2.8	3.0			
SiO_2	60.00	62.00	0.90	+13.1	73.1
TiO_2	1.20	1.02	1.10	+0.003	1.20
Al_2O_3	7.50	6.30	1.11	-0.072	7.57
...	...	...	...	...	...
Na_2O	3.50	1.00	3.27	-2.32	1.18
...	...	...	...	...	...
S	0.75	1.25	0.56	+0.72	1.42
...	...	...	...	...	...
V	300	250	1.12	-5.3	295
...	...	...	...	...	...
Cu	100	600	0.16	+607	707
...	...	...	...	...	...
Zr	125	108	1.08	+2.3	127

instead the absolute quantity of each element remaining after 100 g of the parent rock was altered. Net compositions are therefore not constrained to a constant total just as the process of alteration is not constrained to a constant mass.

APPLICATIONS

Modern Geothermal Systems

A satisfactory analogue for many epithermal precious metal deposits is found in modern geothermal fields (Goldie, 1985; Panteleyev, 1986). In these, precipitation of precious metals may occur in a number of fairly well defined locations, as, for example, at the level of boiling, where deep neutral-chloride waters mix with near-surface acidic aquifers, or where buffering by CO₂-rich discharges occurs. In the exploration of fossil epithermal systems it may help to attempt to reconstruct the original geothermal flow system, thereby expediting prediction of the location of precious metal deposition sites.

Zonal patterns of alteration style and intensity are necessary for such reconstructions. Lithogeochemical data corrected for mass changes permit this synthesis with much less ambiguity than possible with 'raw' data and when combined with temperature and fluid composition estimates of alteration parageneses using mineral phase relations, isotopic systematics and fluid inclusions constitutes a powerful approach to the exploration of fossil epithermal systems. Unfortunately, in Canadian Shield settings, the nearly universal overprint of metamorphic and deformational effects has disturbed many of the pristine hydrothermal characteristics. Nevertheless, some bulk chemical relationships are amongst the most stable of the original alteration properties so if sampling is conducted with awareness of the possibility of short-range metamorphic redistribution of material, effective reconstructions of alteration patterns may yet be obtained.

Patterns of Geothermal Flow Systems

Geothermal flow systems are predominantly constrained by patterns of permeability. Primary permeability includes intergranular porosity, joints and vesicular or vug porosity as well as bedding planes, unconformities and faults (Browne, 1984). Although such features may influence the flow patterns at an early stage in the development of the system, secondary expressions of permeability typically become the dominant controls as the system develops. Secondary permeabilities may be the result of faulting synchronous with geothermal activity, hydraulic fracturing, secondary joints and hydrothermal leaching (Browne, 1984).

Initial control of hydrothermal flow patterns by primary patterns of permeability is described by Henneberger (1986) for the Ohakuri (N.Z.) occurrence where pervasive alteration attests to high initial permeability. Nevertheless, early precipitation of quartz and adularia lead to a progressive reduction of porosity and sealing of flow channels. Permeability was maintained, however, by the initiation of hydrothermal fracturing as fluids eventually became overpressured. The new fractures served as fluid channels until they too sealed causing further hydrofracturing and the cycle was repeated. The geothermal system went through multiple episodes of silicification, feldspathization and fracturing which ultimately had to be self-sustaining. Elements of this cycle may be typical of many geothermal systems.

For fossil systems, patterns of alteration intensity and rank comprise the *prima facie* evidence for the former hydrothermal plumbing system and, as noted above, are outlined by the their mineralogical and geochemical expressions.

Patterns of Hydrothermal Alteration

Hydrothermal alteration effects are controlled by variables such as (a) temperature, (b) pressure (to the extent that it controls the depths at which boiling occurs), (c) parent rock type, (d) reservoir permeability, (e) fluid composition, and (f) duration of activity (Browne, 1984). Of these, items (a), (b) and (e) are the most important in predicting possible zones of precious metal precipitation. They can be outlined by petrographic and geochemical methods (Ewers and Keays, 1977).

A large volume of literature exists describing and explaining the mineralogical expressions of hydrothermal alteration; some of the principal references are by Browne (1978, 1984), Ellis and Mahon (1977), Giggenbach (1981), Hemley *et al.*, (1980), Henley (1985), Henley and Brown, (1985), Henley and Ellis (1983), Henley and Hedenquist (1986) and Rose and Burt (1979). Unfortunately there has been relatively little work done on systematizing geochemical diagnostics of hydrothermal alteration facies.

Browne (1984) notes that the most important minerals relating permeability to alteration in geothermal systems are the feldspars. With increasing permeability (presumably secondary permeability) the feldspar species change from primary intermediate plagioclase, through albite, albite + adularia to adularia. Geochemically, this sequence is expressed in increasing K₂O/Na₂O ratios although in alteration where K-rich illite or interlayered K-illite-montmorillonite are formed the K₂O values do not outline the adularia-enriched alteration zones as effectively.

Fluid compositions can sometimes be predicted from their alteration effects. The quartz-adularia facies noted above is typically a product of the neutral-chloride fluids that characterize the deep fluids in most geothermal systems. Steam separation on boiling partitions most of the dissolved gases like CO_2 , H_2S , H_2 and CH_4 from the liquid. If these gases encounter near-surface groundwater they produce a *steam-heated groundwater* (Henley and Hedenquist, 1986). If oxidized in this environment the H_2S creates an *acid sulphate* fluid with pH as low as 2 which rapidly attacks most minerals (especially volcanic glass) to form deposits of kaolinite, alunite, sulphur, anhydrite, pyrite etc. High Al_2O_3 , SO_4^{2-} and S^{2-} characterize these facies.

The deposition of gold at depth within geothermal systems is primarily related to boiling and resultant separation of H_2S which destabilizes the predominant bisulphide complexes co-precipitating As and Sb (Seward, 1973). $\text{Au}(\text{HS})_2$ also loses stability and Au may be efficiently scavenged by the colloidal As and Sb sulphides. Concurrent with this process, CO_2 -loss may lead to calcite precipitation and create an additional indication of boiling zones. Similarly, radical changes in fluid composition in boiling zones lead to heavy deposition of quartz and alkali-bearing aluminosilicates. Boiling zones become rapidly sealed and reopened many times by hydrothermal explosions. Intense silicification and potash introduction result in substantial density, volume and mass increases in boiling zones.

Within the surface hot-spring environment Seward and Sheppard (1986) have described the precipitation of tungstates, arsenates, phosphates, molybdates and vanadates onto colloidal ferrihydrite ($5\text{Fe}_2\text{O}_3 \cdot 9\text{H}_2\text{O}$). In the example they described (Waimangu, N.Z.) gold was not a notable accessory but it is enriched in other similar situations. CO_2 -loss in boiling springs buffers the waters to a pH about 5 and also promotes the destabilization of Au-complex sulphide species leading to Au precipitation as in the Champagne Pool, Waiotapu (Hedenquist and Henley, 1985; Goldie, 1985) and Ohaki Pool, Broadlands, N.Z. (Weissberg *et al.*, 1979).

Magnitudes of Density, Volume and Mass Change Ratios

Density, volume and mass changes in the rocks that host geothermal systems may be relatively large inasmuch as the host rocks may include highly porous tuffs, ash-flows, hydrothermal breccias as well as more dense welded tuffs, ignimbrites and flows. Some of the primary rocks are likely to be hyaloclastites and very susceptible to hydrothermal alteration. The density, volume and mass change systematics for 85 samples of epithermally altered rocks from New Zealand and the Philippines are illustrated in Figure 1. These data give only broad indications of the range of effects and include host rocks which range from andesites and hypabyssal porphyry to rhyolitic ignimbrite. Alteration intensities range from slight to complete and alteration ranks from the hydrothermal equivalents of zeolite to hornblende-hornfels facies.

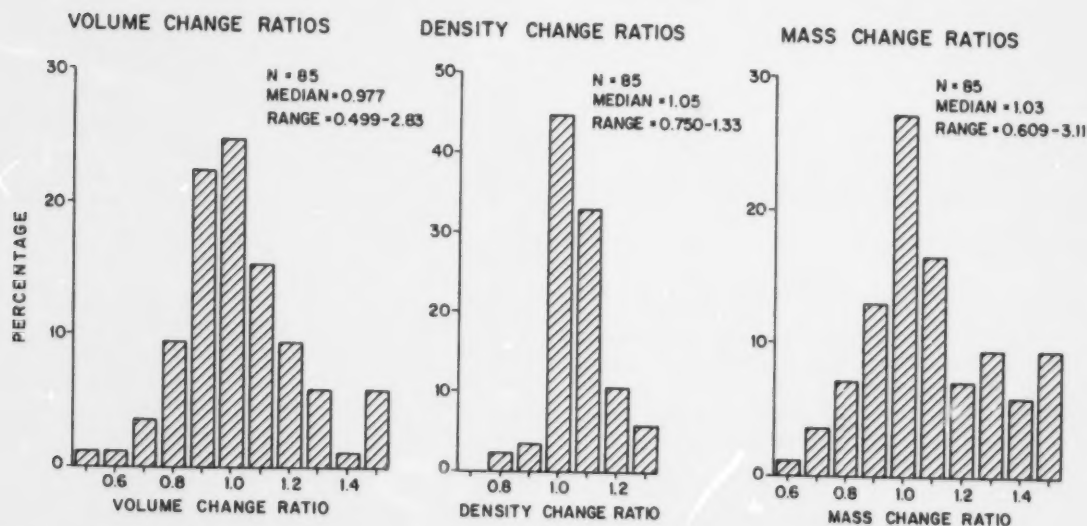


Figure 1 - Histograms of volume, density and mass change ratios for four suites of hydrothermally altered rocks from active and recently dormant geothermal areas in New Zealand and the Philippines. Two samples plot above the range of the volume and mass change histograms.

Median density changes are slightly positive (+5%), median volume changes slightly negative (-2.3%) and median mass changes slightly positive (+3%). The mass change data are skewed in a positive sense by the inclusion of 21 samples from one locality where most samples come from the zone of boiling and indicate a median mass increase of +25%. This particular anomaly indicates the ability of volume, density and mass change data (notably the latter) to outline zones of leaching and of precipitation. Large ranges are the rule with these data and point to the need to consider the spatial distribution of samples in order to portray patterns of zonation.

Illustrations

To illustrate the geochemical effects of alteration with respect to their supposed *intensity* involves the identification of indices that objectively order the samples into correct intensity sequences. Spatial variations in the style of alteration, even within a single alteration system, may require different indices to achieve such rankings.

An example is illustrated (Figure 2) that shows the behaviour of Rb with respect to *propylitic* alteration due to neutral-chloride waters and *base-leaching* alteration caused by steam-heated acid waters. In the former case (Figure 2a), four suites of samples are arrayed in order of their Alkali Alteration Indices which are calculated by taking the logarithm (base 10) of the ratio between $K / (K + Na)$ of the altered rock and the parent rock respectively. This expresses the rate of increase of K with respect to Na, a relatively simple indicator of the intensity of neutral-

chloride alteration. As expected, Rb increases in parallel with the increase in K.

In the case of alteration by acidic waters (Figure 2b), the index chosen is one which illustrates the leaching effect of the acidic waters on the base elements of the host rock. The Base Leaching Index (BLI) is computed as follows:

$$BLI = 1 - \frac{(\Sigma Fe + Mn + Mg)^\beta}{(\Sigma Fe + Mn + Mg)^\alpha} \quad (7)$$

The samples are thus arrayed in order of decreasing amounts of the base elements Fe, Mn and Mg. Rb and most of the other alkalis were subjected to leaching as well.

Mobility patterns of base elements and alkalis can thus be used to define areas of neutral-chloride alteration and acidic alteration very effectively; this might constitute an initial step in outlining alteration patterns with the goal of predicting gold deposition sites.

The Goldfields Granites

The Goldfields Granites (Figure 3) constitute three granitic bodies with many common characteristics surrounding Lodge Bay on the north shore of Lake Athabasca. They are regarded by Macdonald (1987) as part of the **North Shore Plutonic Suite** which has been tentatively dated from ca. 2350 to 2000 Ma (Persons, 1983). They are named the Athona, Box and Frontier Granites respectively. All three host Au mineralization and have accordingly been intensively

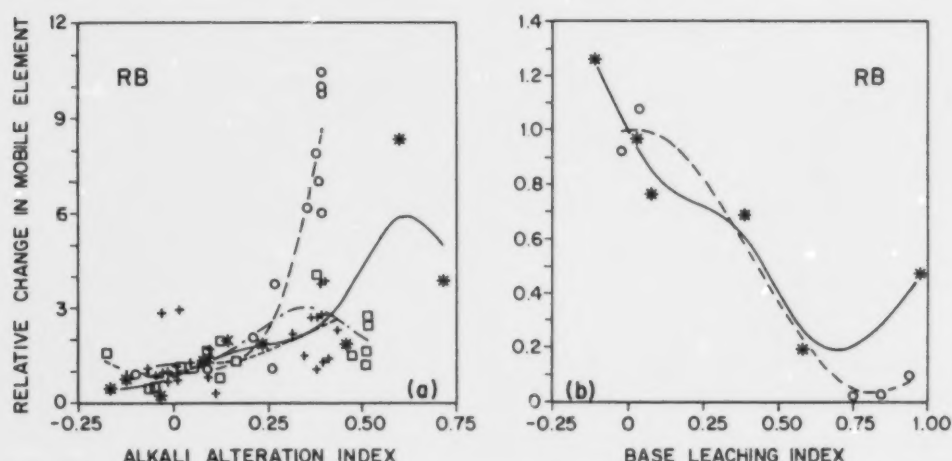


Figure 2 - The distribution of Rb in rocks altered in geothermal systems. Compositional changes are expressed as the net composition levels of Rb relative to the average amount in the respective protoliths. (a) Propylitic alteration by neutral-chloride waters. (b) Base-leaching by acidic waters. Solid line/stars = Bacon-Manito, Philippines; long dash line/circles = Okahuri, N.Z.; dash-dot line/crosses = Waiotapu, N.Z.; short dash line/squares = Tauhara, N.Z.

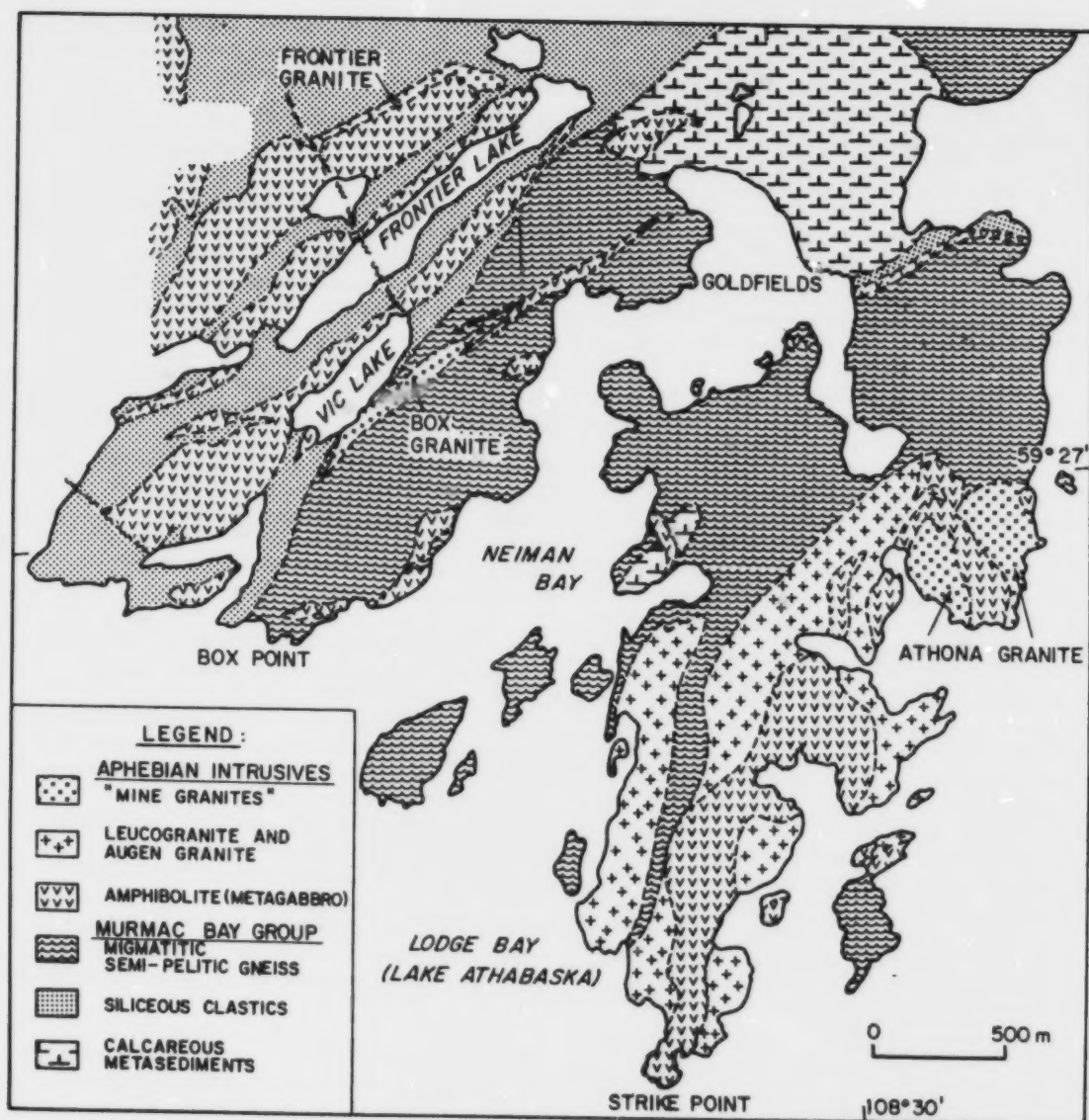


Figure 3 - Location and regional geological setting of the Goldfields Granites, Lake Athabasca, Saskatchewan.

prospected at several times since the initial discovery in 1934. The Box Mine produced gold from 1939 to 1942 when it closed due to war-time labour shortages (Jewitt and Gray, 1940). It is currently undergoing intensive evaluation for possible open-pit production. The Athona property was explored by underground development during 1937 and 1938 but never brought into production (Jiricka, 1984). The Frontier occurrence was also trenched, drilled and explored by about 300 m of underground development in 1935 to 1937 and explored again in the early 1980's; no decision to proceed to development resulted in either case.

Reprise of the 'Granite Problem'

Appleyard (1989) previously summarized the genetic controversy that has raged over these three bodies. In brief, genetic models have ranged from conventional magmatic intrusion (Jewitt and Gray, 1940), through various *granitization* models involving metasedimentary and sheared basic intrusion protoliths (Swanson, 1938 quoted by Mason, 1989; Jiricka, 1984; Sibbald and Jiricka, 1986; Quirt and Rees, 1987). Mason (1989) advanced an isochemical anatectic model which proposed that the Box Granite, and probably the Athona too, originated by

in situ partial melting of an arkosic lens of composition approaching that of the Tuttle and Bowen 'residua' system. This controversy and dispute over fundamental models of granite petrogenesis is strongly reminiscent of the so-called 'granite problem' that raged from the late 19th century to the early 1950's and which has been reviewed so eloquently by Read (1957). The currently pertinent questions concerning these granites include to what extent are they truly magmatic, to what degree have they been affected by co-genetic post-magmatic hydrothermal processes, to non-co-genetic post-magmatic processes? If the granites are 'magmatic' what was their source and how did the magma originate and evolve once it achieved independence of chemical evolution? How did the genetic history of these rocks affect the subsequent concentration of the gold that they contain?

The importance of genetic models to mineral exploration resides in their influence on the development of effective exploration strategies. In this case, the gold is known to be spatially associated with the three Goldfields granites although gold is associated with other rocks in the region (see below). If the Jewitt and Gray (1940) magmatic model is correct then the gold was presumably introduced within the granitic melt and its present distribution is a function of late-magmatic or post-magmatic redistributive processes. If the Mason (1989) anatectic model for the granites is correct, the gold now in the granitic rocks was presumably inherited from the arkosic protoliths. A logical extension of this model would be to explore the quartzose clastics for possible placer gold concentrations. If the hydrothermal models are correct then exploration methodologies should be oriented to uncovering the ancient flow systems through their zoned alteration aureoles. All three models must be extended to take into account the effects of superimposed metamorphic and dynamic events. To date, the influence of later dynamic processes in forming structures has not played a prominent role in formulating exploration strategies but the gold-bearing veins are clearly hosted in late dilatant fractures and the development of these structures is crucial to their current distribution (Roberts and Tyedmers, 1988).

Mineralogical and Geological Relationships

The so-called Frontier 'granite' is the best studied occurrence from a geochemical point of view (Appleyard 1988, 1989, 1990; Quirt and Rees, 1987). The host rock has been termed 'granite' by some earlier workers but there is extremely little rock of granitic character that appears to have gone through the process of crystallization from a melt. Rather, the sequence that is mineralized comprises a stratigraphic package of (a) white, rarely pebble-bearing quartzite, (b) hematitic, locally brecciated quartzite, (c) calc-silicate-bearing quartzite, (d) argil-

laceous quartzite/meta-siltstone, grading towards muscovite-chlorite schist, and (e) arkosic, potassium feldspar-rich quartzite (Appleyard, 1989).

Granite of igneous aspect is restricted to quasi-conformable veinlets and veins (typical thickness 1-2 cm, maximum thickness ca. 1 m) which can be observed to wedge apart sedimentary layers. The host metasediments, however, have been variably silicified (including quartz veining as well as dispersed introduction of quartz), feldspathized, hematized, chloritized and pyritized. All these phenomena are believed to be secondary phenomena dating from a syn-metamorphic period; the 'granitization' effects are intensely developed in places to the point where the palimpsest sedimentary character has been largely lost. The whole sequence is capped by a thick amphibolite sill in which the lower margin has been extensively transformed to biotite-rich schist where involved in the granitization process. Gold mineralization is reported by Jiricka (1884) to be controlled both by stratigraphy and cross-structures attributed to regional folding.

The small amount of igneous-looking granite at the Frontier occurrence is compositionally similar, though not identical to the granites at Box and Athona (Table 2). The mineralogical and chemical parallels amongst these three granites are so close that they must be regarded as co-genetic. Field observations at the Frontier occurrence indicate that a small amount of apparently magmatic granite was tectonically injected into a psammitic sequence of sediments under conditions of thermal harmony. The magmas were accompanied or succeeded by an abundant hydrothermal phase that effected an extensive granitization on the host metapsammities. Gold was introduced sometime during or following this process or was inherited from the host psammities.

The role of mass balance geochemistry in this case is to establish whether the geochemistry is in accord with the model based on megascopic and petrographic observations and to derive any additional information that will elucidate the origin of these rocks and their included gold. Specifically, a metasomatic assessment should be able to distinguish whether gold was introduced from an external source or inherited from the protoliths.

Lithochemistry of the Frontier Granite

This subject was treated briefly before (Appleyard, 1988) prior to outcrop investigation. Two end-member lithologies are clearly present, the variable sequence of metapsammities and the discrete granite veins, between which are the various granitized host-rocks. The samples were accordingly grouped into quartzite, granite and transitional

Table 2 - Mean compositions of Goldfields Granites. * = values by difference from 100%. Units for SiO₂ - S, wt.%; Li - U, ppm; $\bar{x}$ = mean; c = coefficient of variation (SD/mean).

	Box Granite		Frontier Granite		Athona Granite	
n	6		8		5	
	$\bar{x}$	c	$\bar{x}$	c	$\bar{x}$	c
S.G.	2.64	0.01	2.63	0.00	2.62	0.00
SiO ₂	77.20	0.01	81.6*	0.04	76.60	0.02
TiO ₂	0.10	0.26	0.05	0.32	0.06	0.10
Al ₂ O ₃	11.48	0.06	8.4	0.14	11.80	0.07
Fe ₂ O ₃	0.89	0.19	0.85	0.30	0.33	0.51
FeO	0.3	0.47	0.5	0.48	0.6	0.20
ΣFeO	1.08	0.12	1.30	0.35	0.89	0.06
MnO	<0.01	—	0.003	0.47	0.02	0.46
MgO	0.31	0.28	0.24	0.82	0.41	0.04
CaO	0.06	0.25	0.08	0.72	0.35	0.51
Na ₂ O	2.97	0.16	0.31	0.13	3.48	0.05
K ₂ O	4.45	0.09	6.35	0.13	4.29	0.11
P ₂ O ₅	<0.02	—	0.03	0.29	<0.02	—
LOI	1.09	0.18	—	—	0.89	0.17
S	0.061	0.32	0.049	1.16	0.013	0.76
Li	2	0.65	4	0.74	4	0.13
Be	<1	—	<1	—	2	0.18
B	27	0.72	20	0.52	6	2.07
Sc	1.6	0.10	—	—	1.2	0.08
V	14	0.40	10	0.76	9	0.80
Cr	94	0.18	143	0.99	120	0.06
Co	0.7	1.14	3	0.39	1.0	0.18
Ni	3	0.26	6	1.13	2	0.50
Cu	12	0.59	7	0.71	5	0.66
Zn	16	0.66	5	0.47	34	0.43
As	3	0.60	2.4	0.65	1	0.61
Se	<0.5	—	0.2	0.31	<0.5	—
Br	0.8	0.28	—	—	0.7	0.62
Rb	140	0.11	170	0.12	152	0.23
Sr	21	0.17	35	0.24	17	0.31
Y	32	0.19	4	0.44	29	0.21
Zr	133	0.21	82	0.45	79	0.17
Nb	12	0.14	—	—	14	0.21
Mo	2	0.90	<5	—	1	0.39
Ag	0.2	0.84	0.2	—	0.1	1.67
Cd	<1	—	—	—	<1	—
Sn	7	0.61	—	—	4	0.68
Sb	0.4	0.24	—	—	0.3	0.13
Cs	0.4	0.54	—	—	0.4	0.66
Ba	320	0.18	726	0.91	128	0.21
La	25	0.48	16	0.52	16	0.14
Ce	57	0.42	35	0.46	38	0.13
Hf	5.0	0.10	—	—	3.4	0.11
W	3	0.92	—	—	<1	—
Au	0.068	1.18	0.062	3.51	0.015	5.83
Hg	0.005	—	—	—	0.006	0.32
Pb	17	0.92	16	0.11	11	1.51
Th	21	0.12	7	0.77	23	0.22
U	7.6	0.30	1.8	1.44	6.8	0.64

categories. The quartzites are extremely variable, which is reflected in very large variances for individual elements with respect to the mean metasediment composition (Table 2). The initial variances result in considerable uncertainty in identifying immobile elements in individual samples, but because there is a large enough collection of transitional and granite analyses, consistent associations for FV⁰ values of certain elements can be detected and these provide satisfactory immobile elements identification. In this suite the following elements were identified as immobile with decreasing levels of reliability: Y, La, Zr, Ce, Ti, P, Dy, Yb and V.

Magnitudes of Density, Volume and Mass Change Ratios

Because of the uncertainty of matching individual samples of the transitional and granite rock-types to their specific sedimentary protolith it is not appropriate to illustrate the distribution of density, volume and mass change ratios in the form of a histogram. Instead means are given in Table 3 for ten transitional and eight granite samples.

Table 3 - Mean density, volume and mass change parameters for granitized metasediments from the Frontier occurrence (from Appleby, 1988).

	Transitional	"granite"
Density Change Ratio	1.002	0.990
Volume Change Ratio	1.571	2.526
Mass Change Ratio	1.571	2.499

All the samples consist essentially of various proportions of quartz, potassium feldspar, albite, muscovite and/or chlorite and various accessory minerals and consequently they differ little in their densities. Thus mean density change ratios for the transitional and granite samples with respect to their quartzite protoliths are virtually 1.0. Volume and mass change ratios, which under these conditions will be essentially identical, indicate a very different picture however. The transitional samples show a mean increase in volume/mass of 57% while the granite samples have increased approximately 150%. These data are consistent with genetic processes such as injection of magmatic granite and dilational hydrothermal granitization but they do not support the model of *in situ* anatexis.

Recrystallization processes that proceed under the elevated pressures of medium- to high-grade regional metamorphism tend to involve replacement processes that conserve or reduce volume while, in some instances, concomitantly increasing density in accordance with Le Châtelier's rule. In this case, the large mass increase and field relationships require an approximate doubling of the mass of the rocks within

the mineralized zone by the injection of fluids from an external, apparently magmatic, source.

Illustrations

The question of selecting a suitable *granitization index* to arrange the Frontier specimens in a realistic sequence of granitization intensity can be approached in two ways. It was pointed out in Appleyard (1988) that during the granitization process, the metasediments change from muscovite-chlorite-rich assemblages to predominantly feldspathic assemblages. The ratio of alkalis to aluminum therefore can be used to track this change and can be defined as a granitization index as follows:

$$\text{Granitization Index} = (K + Na + 0.5Ca)/Al \quad (8)$$

All values are in molar amounts. The distribution of gold in the Frontier *transitional* and *granitic* rocks is illustrated in Figure 4A and 4B with the data arranged in terms of the Granitization Index defined above. Figure 4A illustrates the data corrected for mass changes and Figure 4B contains the *raw* data.

The second approach to a granitization intensity index makes use of the fact that the granitization process is known from above to involve major mass increases. One can therefore utilize the volume change factor (FV) or the mass change factor as the index. The collective effect of all elemental additions is summed up in these two factors. Accordingly, the data was indexed by Volume Change Factor in the metasomatic variation diagrams published in Appleyard (1988). The distribution of gold in the Frontier granitized quartzites is illustrated according to this index in Figure 4C.

The distributions of data in Figures. 4A and 4B are not greatly dissimilar to the eye, with the exception of the three highest values of the corrected data (Figure 4A) which plot at obviously higher Y-axis values than the comparable raw data (Figure 4B). However, linear regression lines, with 95% confidence limits on mean predicted values, indicate a significantly stronger introduction of gold into the rocks during granitization for the corrected data versus the raw data. The diagram which uses the Volume Change Factor for the X-axis however, displays the trend of

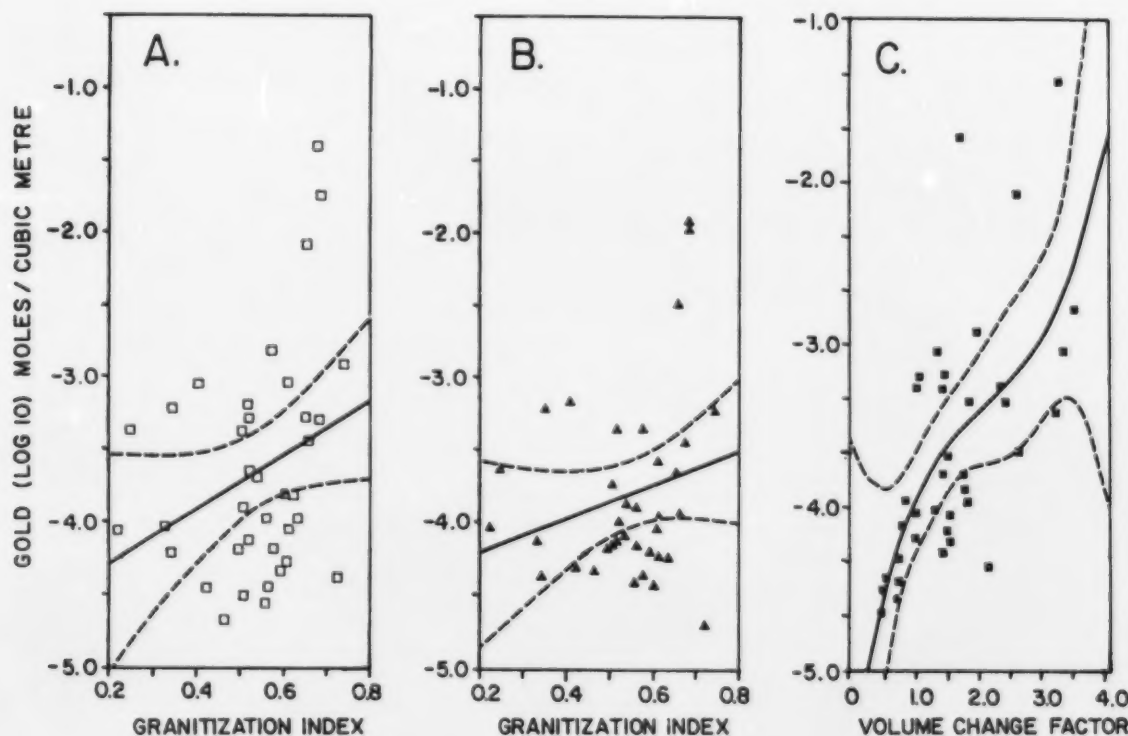


Figure 4 - Distribution of Au in the 'transitional' and 'granitic' granitized metapsammities of the Frontier 'granite' occurrence. A. Data corrected for density and volume changes (net compositions) plotted against the Granitization Index defined in equation 7. B. 'Raw' data plotted against the same Granitization Index. C. Corrected (net composition) data plotted against volume change factors (FV values).

increasing gold in a much stronger manner (the trend lines on this diagram consist of the cubic regression line with 95% confidence limits on mean predicted values).

The pattern of the raw data arranged by the Granitization Index, if examined by eye, could easily be interpreted as showing no introduction of gold during granitization but with three specimens showing aberrant 'nugget' effects. The data in Figure 4A suggests slightly more strongly that gold has been introduced during granitization (the three high values are less likely to be disregarded as anomalous), but the distribution in Figure 4C makes it quite clear that gold introduction was progressive during granitization and must have been genetically associated with that process. Figure 4, therefore, illustrates a case where the practical difference between *raw* data and *net compositions* is made clear and also shows the importance that careful selection of an alteration intensity index has on the eventual interpretability of the resultant variation diagram.

Applications to Mineral Exploration

The ready availability of rock analyses comprising 60 or more elements with sensitivities in many cases into the ppm or even ppb ranges and the parallel availability of relatively powerful computing facilities on even modest budgets are two developments that have revolutionized the role of lithogeochemistry in mineral exploration. These advances permit the acquisition of abundant rock chemistry data of excellent quality and provide the means to process them in a variety of rapid and highly sophisticated ways. This paper has attempted to illustrate that mass balance corrections to lithogeochemical data should be amongst the tools used by exploration geologists to investigate altered and potentially mineralized rock systems.

The advantages reside in three areas:

1. the ability to identify immobile elements by an objective method;
2. the ability to identify the volume and mass change systematics of altered rocks on a sample by sample basis;
3. the ability to recalculate the analyses as *net compositions* which quantitatively express the amount of all elements remaining after the alteration of the protolith.

Immobile elements are used in a variety of applications in lithogeochemistry, notably to assess the original (pre-alteration) lithological character of altered rocks. The use of a wide variety of element ratios to suggest the tectonic settings under which lavas have been erupted is one application. In altera-

tion studies characteristic suites of immobile elements may provide the only basis for matching strongly altered samples with their appropriate protoliths in situations where stratigraphic or structural methods fail. In addition, the recognition of immobile elements is essential in mass balance studies because they provide the means of identifying the Volume Change Factors for each sample.

Despite the wide-spread application of immobile elements their identification has always been a problem and most investigators have resorted to unsatisfactory assumptions based on supposedly close analogies with suites of rocks elsewhere. The Gresens procedure, however, provides an objective procedure involving the calculation of *zero change volume factors* (see equation 5) whereby, in most cases, immobile elements can be identified with relatively little uncertainty. This is the first stage in conducting a mass balance appraisal, but the process is available for other applications where immobile elements are utilized. The use of equation 5 makes this process simple and the FV^0 values can be readily plotted on histograms by element symbol to expedite the identification process but alternative techniques based on the same relationship are available (Grant, 1986).

In providing a method of identifying volume change and mass change factors, the Gresens equation provides a unique and valuable service. Mass changes sum up the total effects of alteration and thus provide a very useful parameter by which the overall effects of alteration can be portrayed. As seen in Figure 4 volume change factors can be used directly as indices of alteration intensity (in this case volume and mass change parameters are virtually identical). Volume change parameters may additionally indicate regions within alteration zones where large volume changes have taken place. In addition, there are theoretical grounds for thinking that areas where strong gradients exist in the volume change patterns might constitute regions where structures may have formed that could have hosted or channelled later mineralizing solutions. Thus, they may have a potential for identifying 'prepared ground'. Mass change maps of epithermal systems have the potential to define areas of boiling, areas of base leaching due to acid waters, and regions of subtle leaching of metallic and other components. This ability to reconstruct the epithermal plumbing system through its geochemical characteristics is particularly useful in regions such as the Canadian Shield where superimposed metamorphic effects may have clouded or obliterated isotopic and fluid inclusion properties which otherwise would provide an excellent ancillary approach.

Finally, the ability to calculate the rock analysis in a form that represents the amount of material remaining after the alteration of the protolith permits the truest manner of representing the effects of the alteration. The procedure has the potential to remove random 'noise' due to density and volume change effects that the raw data inevitably contain. Net composition values enable the geochemist to quantify chemical changes during alteration and thereby to write mathematical expressions of the process that are realistic as well as representative.

Applications in mineral exploration include any procedure where it would be advantageous to use single element results, or quantitative data in a form where ratioing does not remove their absolute values. Spatial distribution maps of single elements within a fence of drill-holes, on a level plan, surface map etc. are obvious applications where net compositions are inherently better at displaying alteration effects than raw data. Net compositions can be used as input data for many software packages that are currently in use in exploration offices designed to illustrate spatial geochemical patterns. Similarly lists of mass and/or volume change factors can be utilized in the same manner.

The examples illustrated above represent cases where the mass balance effects are relatively large; in not all cases are the net effects of the magnitude of those illustrated here. Mass change factors, the most fundamental effect, are represented as the product of volume and density change factors. If volume and density values are symmetrically distributed on either side of 1.0, their product will be close to 1.0, indicating no mass change. Nevertheless, changes in any of the mass, density or volume parameters can be valid indicators of rock alteration effects and should be scrutinized to establish their geological significance.

Applications of mass balance calculations in other fields than mineral exploration *per se* are too numerous to detail but three can be noted because of their relevance to the mineral industry.

Processes of weathering and soil formation are fundamental in the liberation and/or fixing of many elements that have economic significance. Unconformity-related mineral deposits such as the northern Saskatchewan Athabasca Basin uranium deposits are formed in environments where weathering and hydrothermal processes interact (Tremblay, 1983; Sopuck *et al.*, 1983). Large volume and mass changes typify pedogenesis and should be accounted for in establishing elemental distributions in soil profiles as have been illustrated by Macdonald (1980) and White (1985). In addition, the study of soil geochemistry provides information about processes that play a pivotal role in the dispersal of elements in

the weathering environment. This information impinges on the interpretation of many geochemical aureoles.

A special form of weathering studies is that associated with the study of gossans. Although gossans are obvious on the ground and can be detected in many cases by a variety of remote sensing procedures, they need careful study to establish the nature of the sulphide deposit that gave rise to them (Taylor, 1987). The role of mass balance studies in gossans where density, volume and mass changes are all of large magnitudes has been demonstrated by Taylor and Appleyard (1983).

Environmental impact studies of mining operations frequently concentrate on the implications of the ultimate disposal of waste rock and tailings. If these are sulphide-bearing, they react to atmospheric exposure in a manner very similar to natural sulphide-bearing rocks except that their granularity exposes large surface areas to reaction resulting in very rapid oxidation. The vadose zones on tailings and waste rock disposal sites represent sites of currently active weathering. Here, mass balance analyses of the solids complements pore water geochemistry and hydrology in establishing the nature of the reactions taking place and the net input of metals, acidity, etc. to the surface water regime (Blowes, 1990). Applications such as these are likely to play an increasing role in environmental impact assessments in the future and the design of adequate advance and retrospective control measures.

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ACKNOWLEDGEMENTS

The opportunity to study mass balance systematics of active geothermal systems was made possible by the Head of the Department of Geology and the Director of the Geothermal Institute of Auckland University, New Zealand and in particular by Dr. P.R.L. Browne who accepted with equanimity the role of being a mentor in my excursion into the realm of hot-wet alteration. Financial support was generously made available through the Mitsubishi Fellowship.

Study of granitization phenomena associated with the Goldfields granites, Saskatchewan has been supported by the Saskatchewan Geological Survey through Project 3.06 (1989). The continuing interest and valuable insights of Dr. T.I.I. Sibbald are especially acknowledged. Geochemical data from the Frontier occurrence was provided by D. Quirt of the Saskatchewan Research Council and hospitality at the Box Mine Exploration Camp was made available by R.J.K. Mineral Corporation, notably S.J. Carmichael, Senior Geologist.

The development of consistent working methods for computing and interpreting the mass balance systematics of a great diversity of alteration phenomena has been made more fun by the opportunity to work with a large number of undergraduate and graduate students in the course of their studies at the University of Waterloo. Their stimulation and insights have spurred me on, and their pleasures at discovering Nature's meaningful patterns have made the whole learning process enormously enjoyable.

It is a pleasure to acknowledge this assistance.

A COMPARISON OF SURFICIAL GEOCHEMICAL METHODS OF EXPLORATION FOR PLATINUM GROUP ELEMENTS IN CANADA*

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ABSTRACT

Over the past few years a multidisciplinary geochemical study of the platinum group elements (PGE) has been under way at the Geological Survey of Canada (GSC). This includes examination of the distribution and dispersion, as well as the glacial dispersal, of the PGE and associated elements within soils, tills, humus, vegetation and water at a number of locations. The objective is to develop an adaptable methodology that can be used to explore for PGE under variable surficial conditions and depth of burial beneath glacial sediments.

This ongoing study shows that surficial materials and vegetation are effective in identifying areas of concealed PGE mineralization. Various pathfinder elements (e.g. As, Se, Sb and the base metals, particularly in the less than < 2 µm B-horizon soils and tills) may provide preliminary information on the PGE potential of an area prior to undertaking the more expensive precious metal analyses. Both the humus and vegetation appear extremely efficient and cost-effective for identifying broad areas with PGE potential, whereas heavy mineral concentrates from tills are more suitable for zeroing in on PGE mineralization.

INTRODUCTION

Over the past few years a multidisciplinary study of the geochemistry of the platinum group elements (PGE) in the secondary environment has been under way at the Geological Survey of Canada (GSC). This study includes examination of the distribution, as well as the glacial dispersal, of the PGE and associated elements within soils, tills, humus, vegetation and water. The objective is to develop an adaptable methodology that can be used to explore for PGE under variable surface conditions and depth of burial beneath glacial sediments.

Field areas include Ferguson Lake, N.W.T.; Rottenstone Lake, Saskatchewan; and Sudbury, Ontario (Figure 1). Conditions vary from continuous -

discontinuous permafrost to no permafrost, and from arctic desert to boreal forest.

SAMPLE COLLECTION, PREPARATION AND ANALYTICAL METHODS

A variety of surficial sample media and size fractions were collected and prepared. These include B-horizon soil (< 2000 ≥ 180 µm, < 180 ≥ 63 µm, < 180 µm, < 63 µm, < 2 µm); till and gossan (2-6 mm [ground to < 75 µm], < 180 µm, < 63 µm, < 2 µm and heavy mineral concentrate [HMC], S.G. > 3.3); humus (ashed); and several plant species (ashed).

Soil and till samples were collected by profile sampling of hand dug pits or trenches. At Ferguson

*Modified from: Coker, W.B., Dunn, C.E., Hall, G.E.M., Rencz, A.N., DiLabio, R.N.W., Spirito, W.A. and Campbell, J.E. (in press); The behaviour of platinum group elements in the surficial environment at Ferguson Lake, N.W.T., Rottenstone Lake, Sask. and Sudbury, Ont., Canada; in *Geochemical Exploration* - 1989, J. Geochem. Explor.



Figure 1 - Location of the Ferguson Lake, N.W.T.; Rottenstone Lake, Saskatchewan; and Sudbury, Ontario study areas.

Lake, within the zone of continuous permafrost, till sampling was facilitated by the presence of frost boils - sites of periglacial churning that extrude till to the surface.

Each sample of twigs and foliage for a given species consists of material of similar appearance, diameter and number of years growth. The 500 g samples collected at each site were air-dried for several weeks, and then the foliage was separated from the twigs.

Representative samples of the bedrock and mineralization (ground to $< 75 \mu\text{m}$) from each study area were also analyzed. The prepared sample materials were analyzed for:

- 1) Au, Pt, Pd and Rh by inductively coupled plasma - mass spectrometry (ICP-MS) following decomposition by Pb fire assay or HF/aqua regia; or by fire assay - atomic absorption spectrophotometry (FA/AAS);
- 2) As, Sb, Bi, Ge, Se and Te by HCl/HNO₃ digestion - hydride generation - inductively coupled plasma - emission spectrometry (ICP-ES);
- 3) V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Mo, Ag, Cd, and Pb by HCl/HNO₃ digestion - AAS or ICP-ES; and
- 4) S by gravimetry.

The precision and accuracy of all analytical data were determined by the routine insertion and analysis of duplicate and reference control samples.

Vegetation Ash Analysis - Method Development

As the PGEs are generally present in small concentrations in surficial materials, development work on analytical techniques was an essential part of this study. There is a need to provide precise and ac-

curate low level PGE analytical data, particularly for waters and organic media.

Conventional analytical methods used by commercial or high-production laboratories to determine Au, Pt and Pd as a 'package' in ashed vegetation at detection limits that are of value to exploration (1 to 10 ppb) require a sample weight of 10 g (Dunn, 1986a; Hall and Bonham-Carter, 1988). This quantity of ash hinders widespread application of biogeochemistry as an exploration technique for PGE because it requires initial collection of approximately 500 g of twig or 2,000 g of trunk wood. Unfortunately, if the ash weight is reduced to a more practical size of 1 g, detection limits increase above useful exploration levels; this is particularly true for Pd which suffers from high 'blank' concentrations encountered in the fusion process.

An efficient and cost-effective method of determining Au, Pt and Pd down to 1 to 2 ppb in a 1 g sample of ash (i.e. < 50 g of dry twigs) has been developed at the GSC (Hall *et al.*, in press). The sample is decomposed with HF and aqua regia; then the analytes are separated out by co-precipitation on Te, re-solubilized and determined by ICP-MS or GFAAS (graphite furnace atomic absorption spectrophotometry). The Pb fire assay/ICP-MS analyses of control samples containing these elements at high concentrations gives low results for Pd with this new method, unless: a) the sample is ashed at 870°C rather than the conventional 470°C; or b) an additional step of evaporation with perchloric acid (HClO₄) is incorporated. Dunn *et al.* (1988) suggest that a stable Pd complex forms upon ashing at 470°C, requiring either increased heating (i.e. at 870°C, where Pd-O bonding dissociates) or oxidative acid attack for complete breakdown and solubilization of Pd compounds. Ashing at 870°C provides the simplest solution and no loss of analytes in the species studied (spruce, alder, pine, birch and Labrador Tea) by the inclusion of this step. Details of the analytical methods are given in Dunn *et al.* (1988), Hall *et al.* (in press) and Coker *et al.* (in press).

Water Analysis

The method designed to determine Au in waters (Hall *et al.*, 1986) can also be used for Pt and Pd analysis. In summary, Pt and Pd are adsorbed onto 300 mg of activated charcoal from a filtered 1 litre water sample acidified with 10 ml of 12M HCl. The charcoal is filtered off, ashed at 650°C, the analytes solubilized in aqua regia and the solution diluted for analysis by ICP-MS or GFAAS. Detection limits for Au, Pt and Pd are in the range 0.2 - 1.0 ppt.

The deterrent to widespread application of this method is the care that must be taken to maintain Pt and Pd in solution prior to adsorption on activated charcoal. Making the sample 0.1M in HCl ensures stability for at least several months, but transportation of acid in the field is difficult. Probably the easiest approach would be to arrange for delivery of the samples to a base laboratory within 24 hours of collection. The loss of Pt and Pd to the walls of the container is not significant (< 10 percent) in this time period (cf. approximately 80 percent loss in 20 days). Unlike Au, Pt and Pd cannot be fully recovered from the container walls by leaching with Br₂-HCl (Hall *et al.*, 1986). An alternative procedure would be to collect Pt and Pd on the charcoal in the base camp, a relatively simple task, and then to send the samples of filtered charcoal to the laboratory for analysis.

Application of this method to waters collected near known PGE deposits at Ferguson Lake resulted in detection limits being lowered by a factor of 10, to 0.02 - 0.1 ppt. Although extremely low, detectable concentrations of Pt (2.8 ppt) and Pd (2.0 ppt) are present in waters adjacent to the gossanous zones at Ferguson Lake; background levels of 0.2 ppt exist only a few metres away.

RESULTS AND DISCUSSION

Results from the three areas investigated - Ferguson Lake, Rottenstone Lake and Sudbury - are presented. As this project is still ongoing the results, interpretation and conclusions presented are only preliminary.

Ferguson Lake, Northwest Territories

General Geology and Mineralization

Bedrock is dominated by east-northeast-striking hornblende-rich gneisses, amphibolites, and granitic gneisses. The gneisses are possibly volcanic and sedimentary rocks of the Archean Kaminak Group (Davidson, 1970) that were metamorphosed during the Hudsonian Orogeny (Bell, 1971).

Copper-nickel sulphides form narrow, massive lenses and disseminations in a thin unit of coarse hornblende, which strikes east and dips north at 35° (Wright, 1967; Leggett *et al.*, 1976). The metallic minerals present in near-surface samples are, in decreasing order of abundance: nickeliferous pyrrhotite, marcasite, goethite, chalcopyrite, magnetite and pyrite. The massive sulphides contain 1.2 to 3.3 percent combined Cu and Ni. The mineralized zones on the east and west sides of Ferguson Lake are marked by spectacular gossans several hundred metres long by up to 25 m wide.

Surficial Geology

The surficial geology of the Ferguson Lake area is dominated by constructional glacial landforms, except on the uplands where thin drift and bare bedrock are common (Aylsworth *et al.*, 1981). The only indicated ice flow direction is to the southeast. This area is within the zone of continuous permafrost, where till sampling is facilitated by frost boils.

Till and Gossan Geochemistry

Previously DiLabio (1979) found only limited base metal dispersal in the tills, but in a preliminary study of the distribution of the PGEs and Au in the gossan, DiLabio (1988) found that palladium was more concentrated in the finer size fractions, whereas platinum was erratically distributed as micronuggets.

As part of a geochemical research project in the N.W.T. (Coker *et al.*, 1988), six trenches were excavated in the gossanous till/bedrock zone over the PGE-bearing nickel-copper mineralization. Grab samples of the gossanous bedrock contained up to 70 ppb Au, 590 ppb Pt, 2500 ppb Pd, 9000 ppm Ni, > 2 percent Cu, 45.0 percent Fe, 500 ppm Mn, and 250 ppm Cr. Data for the < 2 µm, < 63 µm, < 180 µm, 2-6 mm and HMC fractions of the gossanous till from Trench 2 (Figure 2) and Trench 5 (Figure 3) illustrate the general distribution patterns in profile form for Au, Pt, Pd, Ni, Cu, Fe, Mn, and Cr.

Gold profiles are relatively consistent for all the fractions (Figures 2 and 3), but maximum concentrations occur mostly in the finer (< 63 µm or < 2 µm) fractions. The lowest Au concentrations occur in the coarse (2-6 mm) and HMC fractions (Figures 2 and 3).

Platinum shows greater variation between fractions (Figures 2 and 3). Maximum concentrations of Pt clearly occur in the HMCs; all other fractions have at least an order of magnitude less Pt, with lowest concentrations generally present in the < 2 µm material.

There is a strong similarity of profiles for Pd in the different fractions (Figures 2 and 3). Maximum Pd occurs in the < 63 µm, < 2 µm and HMC fractions, and minimum Pd occurs in the 2-6 mm fraction.

Nickel and Cu have consistent distribution patterns for the different fractions (Figure 2 and 3). Nickel and Cu occur at maximum concentrations in the coarse fractions (HMC and 2-6 mm) and minimum concentrations in the fine fractions (< 2 µm and < 63 µm).

Manganese is most concentrated in the coarse fractions (HMC and 2-6 mm), with fine fractions (< 2

FERGUSON LAKE - GOSSAN TRENCH #2

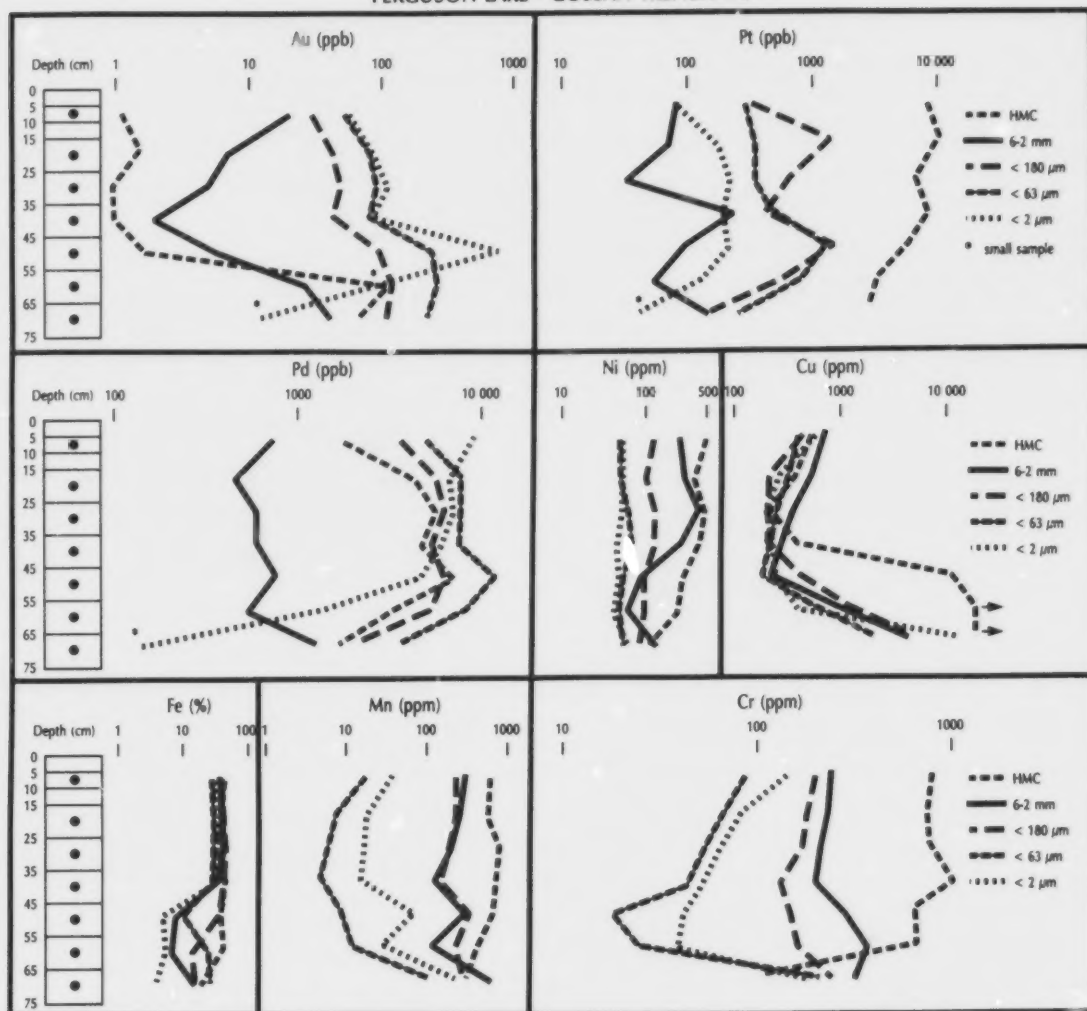


Figure 2 - The distribution of Au, Pt, Pd, Ni, Cu, Fe, Mn and Cr in the <2 μm , <63 μm , <180 μm , 2-6 mm and HMC fractions of gossanous till, Gossan Trench 2, Ferguson Lake, N.W.T. (→ = greater than upper detection limit of 20,000 ppb).

μm and <63 μm) containing one to two orders of magnitude less Mn. Iron also has maximum concentrations in the coarse fractions (HMC, 2-6 mm or <180 μm) and minimum concentrations in the fine fractions (<2 μm and <63 μm), but there is little overall variation for the different fractions. Chromium distribution is almost identical to Mn (Figure 2 and 3).

Based on the distribution patterns for Au, Pt, Pd, Ni, Cu, Fe, Mn, and Cr, it appears that there is a marked degree of surface (supergene) enrichment of all these elements in the gossanous till relative to the underlying mineralized bedrock. There also appears

to be a combination of both clastic dispersal (i.e. preferential accumulation of Pt, Ni, Cu, Fe, Mn and Cr in the coarse fractions) and hydromorphic dispersal (i.e. Au, Pd, Ni and Cu). There is undoubtedly coprecipitation of Ni and Cu (and perhaps Au and Pd) with Fe and Mn hydroxides/oxides in the gossanous till zone. Selective extractions will aid in determining the mechanism(s) of dispersal and accumulation as well as the mode of occurrence of these metals. Also, examination of the mineralogical forms of these elements will help determine the mechanism(s) of dispersal and accumulation. Preliminary searches of the HMCs with a scanning electron microscope have shown that a small number of blocky angular

FERGUSON LAKE - GOSSAN TRENCH #5

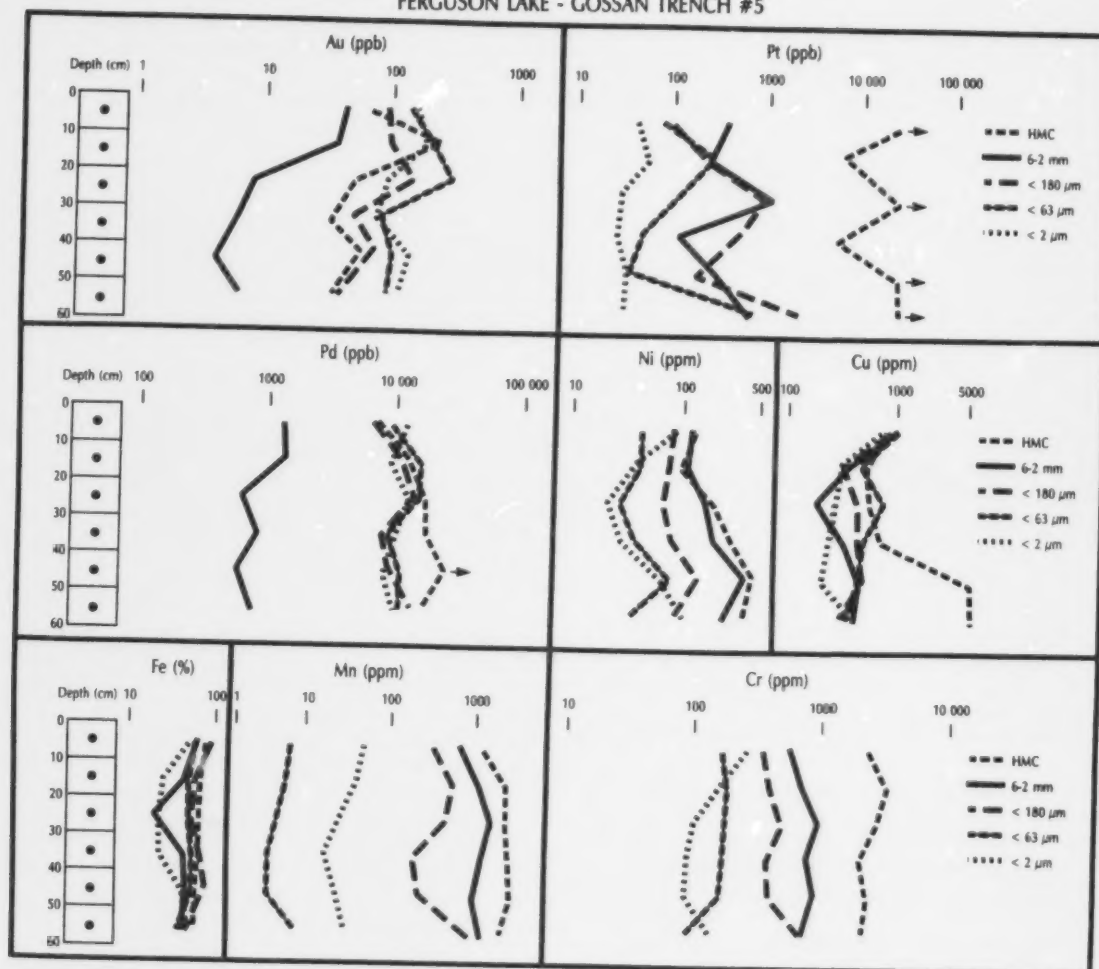


Figure 3 - The distribution of Au, Pt, Pd, Ni, Cu, Fe, Mn and Cr in the < 2 µm, < 63 µm, < 180 µm, 2-6 mm and HMC fractions of gossanous till, Gossan Trench 5, Ferguson Lake, N.W.T. (→ = greater than upper detection limit of 20,000 ppb).

Pd-rich grains are present in the gossan. These grains are mostly < 20 µm in size and contain minor amounts of Bi, Pd and Te.

Although no one fraction of the gossanous till stands out as the optimum sample medium, analysis of the HMC and < 63 µm fractions would seem to provide the best approach to exploring for PGE in this environment. This approach was used, but it proved difficult and costly to recover sufficient heavy minerals from the non-gossanous tills in order to obtain reliable analytical data.

The exposed gossan zones are evident and a possible extension of the mineralization beneath a peat- and

till-covered area to the northeast is suspected. However, there appears to be only limited (100 - 200 m) down-ice dispersal of Au, Pt, Pd, and Cu in the < 63 µm component of the till samples collected from frost boils (Coker *et al.*, in press).

Biogeochemistry

The highest concentrations of Pt, Pd, Rh and Au in Labrador Tea and dwarf birch are found over the gossan. These metals are detectable in plant samples in a zone of glacial dispersal extending only a few hundred metres down-ice, and is very similar to the zone detected by till sampling (Coker *et al.*, in press).

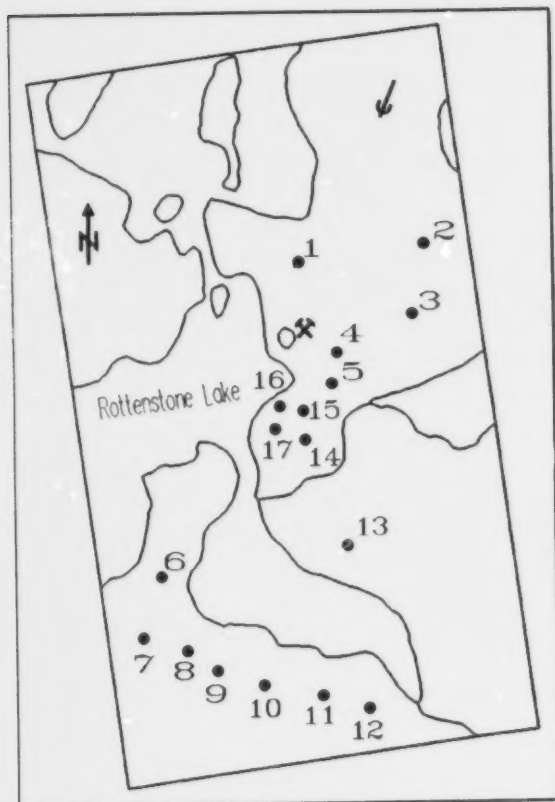


Figure 4 - Sample site location map, Rottenstone Lake, Saskatchewan.

Rottenstone Lake, Saskatchewan

General Geology and Mineralization

Despite its small size, the Rottenstone deposit was the richest PGE and Au producer of any nickel-copper deposit in Canada. For example, in late 1965, 5,500 tons of ore were mined at an average grade of 3.23 percent Ni, 1.83 percent Cu, 4.79 ppm Pt, 3.92 ppm Pd, 1.03 ppm Au and 6.85 ppm Ag. The deposit, which was mined out in 1968, was contained in one of three small harzburgite-orthopyroxenite sill and plug-like bodies. The main ore showing was 50 m long, 37 to 50 m wide and 8 to 12 m thick. Its oxidized cap rose 12 metres above the eastern shore of Rottenstone Lake (Hulbert *et al.*, 1988).

Most of the mineralization was in the form of dense net-textured sulphides in harzburgite, and disseminated sulphides in pyroxenite, with minor massive sulphides in both rock types (Hulbert *et al.*, 1988). PGE were concentrated locally, in sperrylite (PtAs₂), moncheite (PtTe₂) and kotulskite (PdTe) (Hulbert, pers. comm.).

Surficial Geology

The surficial geology is characterized by a thin (generally less than a few metres thick), discontinuous cover of silty-sand till on bedrock ridges. In depressed areas till is interfingered with glaciofluvial and glaciolacustrine sediments. The main ice flow direction was to the south-southwest.

Till and Soil Geochemistry

At each site (Figure 4) a pit was hand dug and samples of the B-horizon soil and underlying till were collected. After drying, one portion of each soil and till sample was separated into the < 2 mm ≥ 180 μm, < 180 μm ≥ 63 μm, and < 63 μm fractions; another portion into the < 144 μm fraction; and the remainder of each till sample was used to obtain a heavy mineral concentrate (HMC - S.G. > 3.3). The quantities of heavy minerals recovered were only sufficient for the determination of PGEs and Au.

Any type of rigorous statistical evaluation of the data is not valid as the sample population is very small (Table 1: n = 17). The distribution of the data was examined and a classification breakdown appropriate to display (Figures 5 and 6) the variation for each element chosen.

Moderate to high concentrations of Pt (up to 4504 ppb) and Au (up to 435 ppb) were found in the HMC of the tills. These values extend for a distance of at least 1 km (the limit of the survey) down-ice from the mineralization (Table 1; Figure 5). At sites 1, 2 and 3, up-ice of the mineralization, precious metal enrichment was found in HMC (Pt up to 197 ppb and Au up to 286 ppb) suggesting there may be an area of bedrock enrichment of these elements north of the known mineralization.

The geochemical data for the separated fractions of soil and till generally show low values for PGEs and Au, with most values being at or close to detection limits. In a few places there are indications of Pd (6 to 31 ppb) and Au (2 to 67 ppb) in different fractions of the B-horizon soil; and of Au (3 to 63 ppb) in the < 63 μm fraction of the till. These correspond to the higher levels of Pt and Au encountered in the HMC (i.e. sites 10, 16 and 17).

Of the base metal and associated pathfinder elements examined, Cu and Ni in the < 63 μm fraction of the till (Table 1) best outline the mineralization and associated glacial dispersion (Figure 5). Although all fractions of the B-horizon soil are similarly enriched, Cu and Ni concentrations increase with fraction fineness (Table 1). Arsenic and Sb may also be useful pathfinder elements in this area, but more work is needed to confirm the observed trends.

Table 1 - The distribution of Pt and Au in HMCs of till and of Cu and Ni in the $<2000 \geq 180 \mu\text{m}$, $<180 \mu\text{m} \geq 63 \mu\text{m}$, and $<63 \mu\text{m}$ fractions of till, Rottenstone Lake, Saskatchewan. For comparison purposes data for Pt, Au, Ni and Cu in ashed black spruce twigs are also given. (See Figure 4 for sample site locations).

Site	Pt (ppb)		Au (ppb)		Cu (ppm)				Ni (ppm)			
	Till HMC	Spruce Twig	Till HMC	Spruce Twig	Till $<2000 \geq 180 \mu\text{m}$	Till $<180 \geq 63 \mu\text{m}$	Till $<63 \mu\text{m}$	Spruce Twig	Till $<2000 \geq 180 \mu\text{m}$	Till $<180 \geq 63 \mu\text{m}$	Till $<63 \mu\text{m}$	Spruce Twig
1	26	154	286	23	45	16	45	237	15	8	18	238
2	197	19	88	21	10	20	37	229	6	9	16	69
3	2	26	253	27	39	51	73	255	18	26	41	112
4	2	468	39	252	8	17	33	1112	12	9	15	605
5	<2	346	33	145	8	13	18	775	7	8	11	571
6	14	4	113	22	10	19	16	192	10	19	15	44
7	515	<2	18	21	6	13	13	132	3	12	12	26
8	20	<2	56	9	7	12	36	176	4	8	22	41
9	274	<2	54	10	5	8	21	187	4	8	24	43
10	878	<2	435	11	10	16	20	253	18	27	34	51
11	47	<2	115	15	5	6	28	261	2	4	16	36
12	139	<2	21	9	6	8	13	183	6	8	15	27
13	107	<2	<2	16	16	23	87	219	3	6	23	76
14	32	<2	43	25	15	27	96	213	4	5	23	222
15	40	294	10	200	8	11	49	902	4	5	17	608
16	4504	41	<2	38	100	167	207	302	98	16	200	260
17	353	<2	58	12	19	26	40	207	19	22	35	116

Biogeochemistry

The mine site has been virtually undisturbed since the open pit operation ceased in 1968, permitting natural seeding and growth of common vegetation species of the northern forest. These include black spruce (*Picea mariana*), jack pine (*Pinus banksiana*), paper birch (*Betula papyrifera*), mountain alder (*Alnus crispa*), pussy willow (*Salix discolor*), Labrador Tea (*Ledum groenlandicum*), and various grasses. Thus the environment is that of a 'natural laboratory', ideal for examining the relative concentrations of a variety of elements in common plant species.

A wide range of precious and base metal concentrations exist in different types of plant tissue, that were collected in late June, 1987 (Table 2). It should be noted that the hierarchy of metal concentrations may shift at other times of the year due to seasonal variations in plant chemistry. This is particularly true for gold in alder, which has appreciably higher concentrations in the spring (Dunn, 1986b; Kovalevskii and Kovalevskaya, 1989).

Several notable features of metal accumulation are evident from Table 2. The PGE and Au are preferentially concentrated in spruce twigs and outer bark, whereas Ag levels are highest in the spruce trunk wood. Copper enrichment is greatest in spruce twigs and outer bark, and in Labrador Tea and grass. Nickel concentrations are highest in twigs of birch and Labrador Tea, and in grass. Data are not included for jack pine because none were present in the immediate vicinity of the other species, but an earlier study (Dunn, 1986a) showed that PGE concentrations in jack pine are similar to those in spruce.

From the information obtained in this comparative study it was evident that in this environment the optimum vegetation sample medium for comparing distributions of PGE with the chemistry of various soil and till fractions would be either spruce twigs or outer bark. Twigs were chosen because it was easier to collect the moderately large volume of sample material needed to provide sufficient ash for research purposes.

Spruce Twig Survey

Approximately 500 g of material comprising the most recent 10 years growth of spruce twigs and needles was collected at each sample location. After several weeks of air drying in a greenhouse, the needles were separated from the twigs, and the twigs were ashed in a kiln at 470°C. The average ash yield was approximately 1.8 percent.

Moderate to strong enrichment of PGE, Au, and pathfinder elements (Se, Bi) in twigs occurs for less than 200 m down-ice of the mineralization (Figure 6 and Table 3). Weak enrichment of Pd and Au occurs at a few of the most southerly sites of the survey area, but the other PGE were not detectable. Both Ni and Cu show similar dispersion patterns to Pd and Au, but Ni is more pronounced. Silver exhibits little variation, except in the immediate vicinity of the mine site.

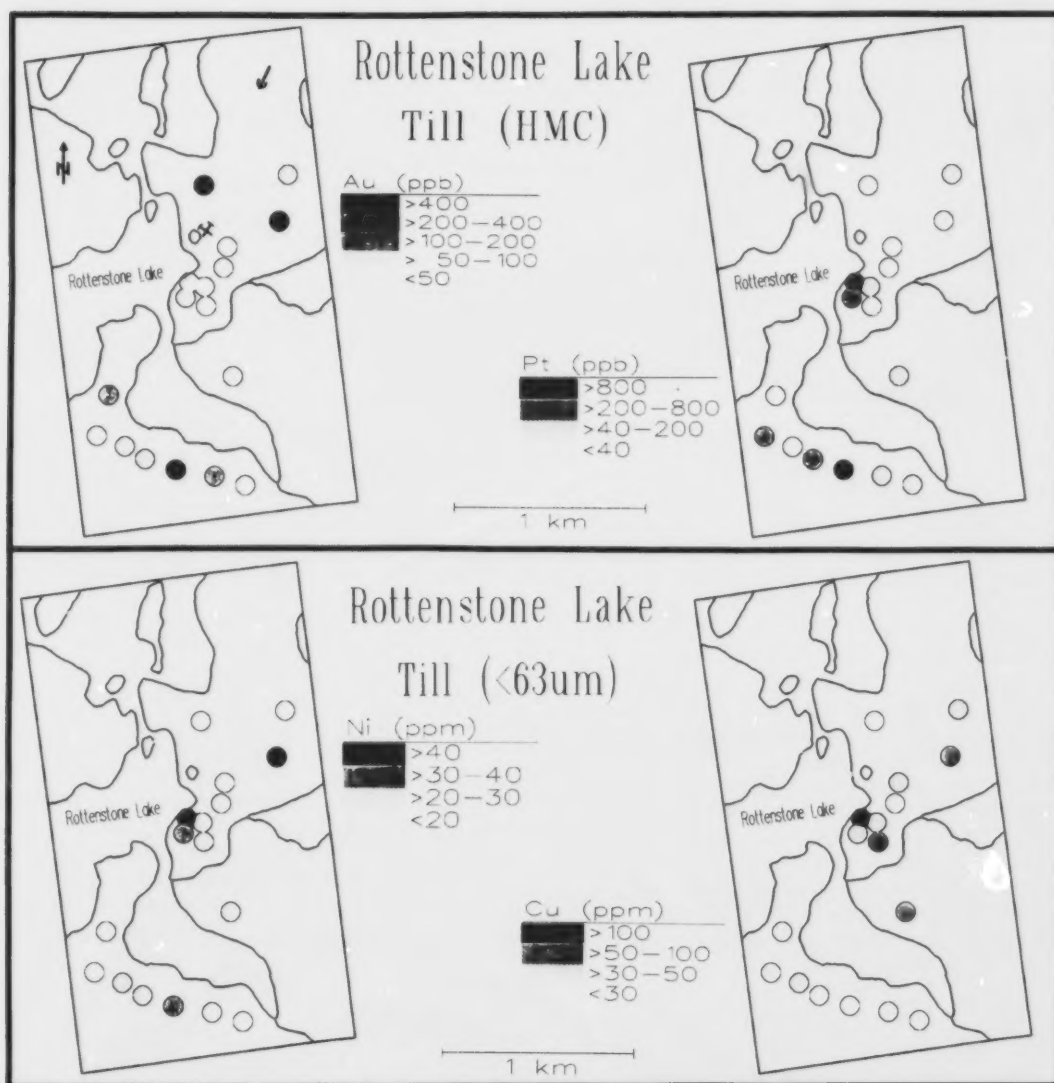


Figure 5 - The areal distribution of Au and Pt in the HMCs of till and of Ni and Cu in the <63 μm fraction of till, Rottenstone Lake, Saskatchewan.

Precious metal enrichment in the twigs is also present north of the mine site (up-ice), reconfirming an earlier observation by Dunn (1986a) and substantiating the HMC results from this study. This suggests that there may be bedrock enrichment of PGE north of the mine site.

In summary there is only limited down-ice dispersal (i.e. up to 200 m) of PGE and Au in spruce twigs, whereas Pt and Au in HMC show greater dispersal of at least 1 km. Thus it appears that only HMC and spruce twigs are of value in detecting Pt and Au in this area. Palladium differs in that it is detectable

only in some of the soils, is absent in the tills and HMC, yet is appreciably enriched in twig ash. The inference is that Pd is moving in solution and is being adsorbed to a slight degree by the soil, but is being taken up much more significantly by the plant roots.

Sudbury, Ontario

General Geology and Mineralization

Sudbury's famous nickel-copper sulphide ores are found along the lower contact of the funnel-shaped mafic intrusion known as the Sudbury Igneous Complex. This intrusion is 60 x 23 km on surface; it is in-

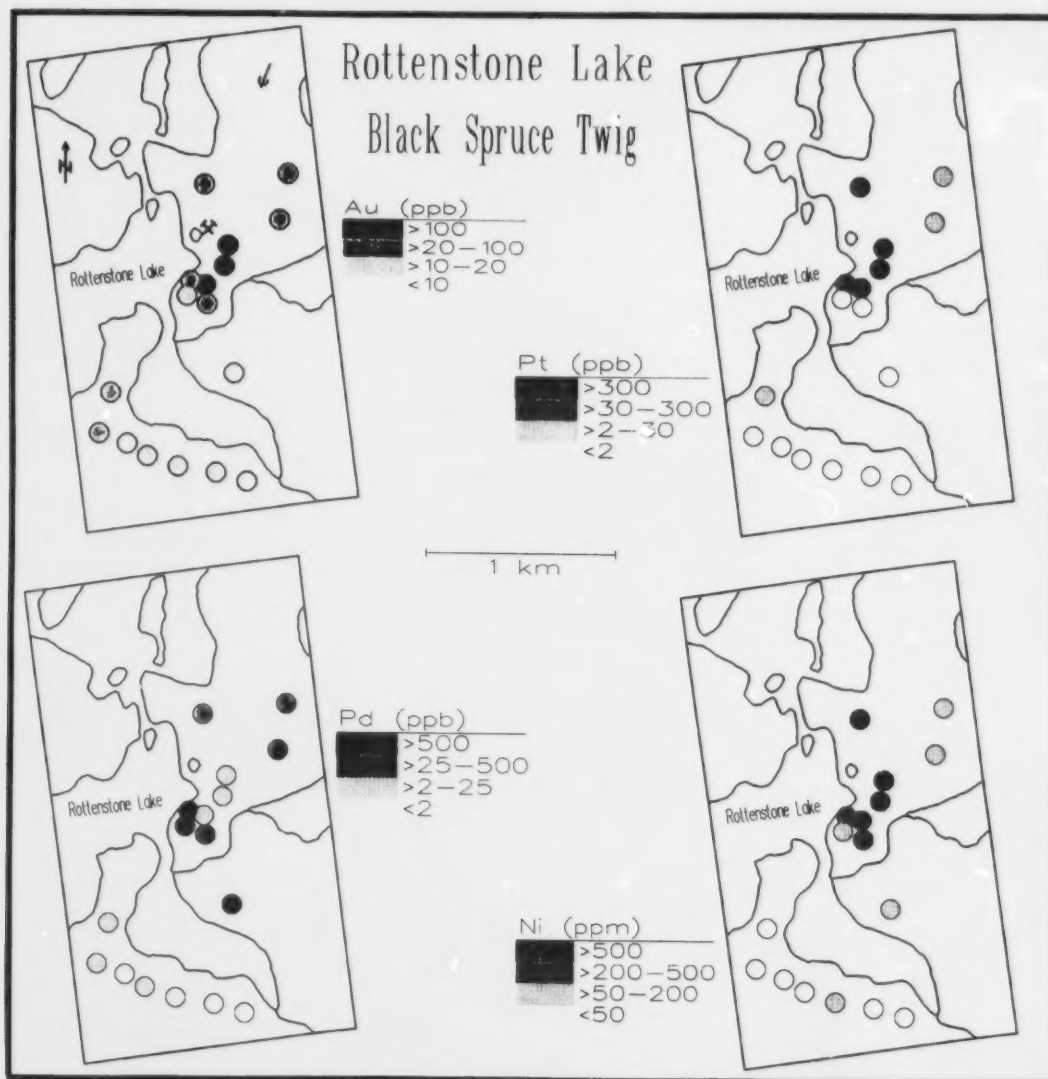


Figure 6 - The areal distribution of Au, Pt, Pd, and Ni in ashed black spruce twigs, Rottenstone Lake, Saskatchewan.

truded into Archean and Proterozoic rocks close to the junction of the Superior, Southern and Grenville structural provinces of the Canadian Shield. In addition to world-class production volumes of Ni, Cu and PGE, the deposits produce significant amounts of Au, Ag, Co, S, Se, Te and Fe (Hulbert *et al.*, 1988).

The two properties sampled in this study are both of the North Range type of mineralization: typically pyrrhotite, pentlandite and chalcopyrite occurring interstitially in a footwall breccia, as inclusion-bearing massive sulphide, and as sulphide clasts in the breccia (Pattison, 1979; Hulbert *et al.*, 1988). Platinum

group elements are present in all Sudbury ores at variable but economically significant levels. Cabri and Laflamme (1984) identified 18 platinum group minerals (PGM) in the ores; Pt, Pd and Rh are known to be present in solid solution in the sulphur-senide minerals. About 90 percent of the Pt and 40 percent of the Pd are present in PGMs; the remainder occurs in solid solution, mainly in pentlandite (Hulbert *et al.*, 1988).

Surficial Geology

The surficial geology of the two properties is characterized by bedrock ridges with a thin (a few metres)

Table 2 - Precious metals (ppb) and base metals (ppm) in ashed plant tissues (single samples) from close to the old mine site, Rottenstone Lake, Saskatchewan (modified from Dunn, 1988).

Sample Medium	Pt ¹ ppb	Pd ¹ ppb	Rh ¹ ppb	Ir ² ppb	Au ² ppb	Ag ³ ppb	Cu ³ ppm	Ni ³ ppm	Ash %
Black spruce twigs	800	1443	72	62	276	4300	1274	858	2.2
Black spruce bark (outer)	1187	1662	57	54	336	3300	1587	962	3.8
Black spruce bark (inner)	126	212	6	<3	40	2500	228	296	3.4
Black spruce needles	83	244	6	<4	49	1900	193	235	4.0
Black spruce trunkwood	89	70	<2	<3	17	15500	227	252	0.37
Birch twigs	125	306	11	<5	57	3600	572	1720	1.0
Birch leaves	87	326	10	<4	54	1500	304	746	4.0
Birch trunkwood	10	45	<2	<5	14	2100	309	509	0.47
Alder twigs	62	170	13	<5	43	1600	565	1090	1.1
Alder leaves	35	158	3	<5	31	900	459	1226	4.4
Willow twigs	16	74	<2	<4	15	600	186	634	1.4
Willow leaves	ND	ND	ND	<4	12	900	159	1276	5.9
Labrador tea twigs	166	368	14	15	70	1800	1327	1876	2.0
Labrador tea leaves	279	499	28	15	104	1000	1160	1187	3.9
Marsh grass	18	30	<2	<7	5	300	1584	3419	6.5
Background concentrations	<5	<2	<2	<2	5-20	<1000	<100	<20	4

ND = Not determined

1 FA/ICP-MS

2 INAA

3 ICP on aqua regia digest

4 Depends on species and tissue type

Table 3 - Element concentrations in the ash of black spruce twigs, Rottenstone Lake, Saskatchewan. (See Figure 4 for sample site locations).

Site #	Pt	Pd	Ir	Rh	Au	Ag	Cu	Ni	Se	Bi
1	154	87	<2	<2	23	3.7	237	238	2.0	.7
2	19	25	<2	<2	21	3.8	229	69	1.4	.5
3	26	92	<2	<2	27	2.2	255	112	2.0	.8
4	468	1318	23	46	252	6.2	1112	605	5.0	3.0
5	346	517	18	20	145	3.7	775	571	5.6	2.3
6	4	8	<2	<2	22	2.7	192	44	1.1	.4
7	<2	6	<2	<2	21	1.3	132	26	1.1	.4
8	<2	8	<2	<2	9	1.1	176	41	.5	.4
9	<2	6	<2	<2	10	2.4	187	43	1.2	.8
10	<2	<2	<2	<2	11	2.8	253	51	.8	.3
11	<2	3	<2	<2	15	2.4	261	36	1.3	.4
12	<2	<2	<2	<2	9	3.0	183	27	1.4	.6
13	<2	<2	<2	<2	16	1.8	219	76	.4	.4
14	<2	<2	5	<2	25	2.0	213	222	1.8	.8
15	294	666	26	32	200	3.8	902	608	6.0	2.4
16	41	60	4	<2	38	2.7	302	260	2.4	1.0
17	<2	5	<2	<2	12	3.1	207	116	.8	.3

cover of silty-sandy till. The till is interfingered with lenses of glaciofluvial outwash material which grades into glaciolacustrine sediments in low-lying areas. The most recent ice flow directions vary from southeast, to south, to south-southwest.

Soil and Till Geochemistry

Sample media at each site (Figure 7) are similar to the other study areas, except no vegetation, other than humus, was collected. Gold and PGE concentrations in all soil fractions show only minimal response to the mineralization. The PGE mineralization is best reflected in the ashed humus (Table 4) but the $< 2 \mu\text{m}$ fraction of the B-horizon soil also contains elevated levels of Ni, Cu, and As in particular (Table 4), as well as Sb, Se, Cr, Co, Pb and Zn. For till, HMC are the only media to show any significant enrichment of PGE and Au. The HMC are also markedly enriched in As, variably enriched in Sb and Se, but the base metal concentrations show no indication of the mineralization (Table 4). The $< 2 \mu\text{m}$ portion of the tills is most enriched in Cu, Ni, As, and Se.

CONCLUSIONS

This ongoing study shows that surficial materials and vegetation are effective in identifying areas of concealed PGE mineralization. Various pathfinder ele-

ments (e.g. As, Se, Sb and the base metals, primarily Cu and Ni, particularly in the $< 2 \mu\text{m}$ B-horizon soils and tills) may be informative in a preliminary evaluation of the PGE potential of an area, prior to undertaking the more expensive precious metal analyses. Both the humus and vegetation appear to be effective and cost-efficient media for identifying and providing an exploration focus on areas with PGE potential. HMC are also effective in reconnaissance scale exploration. Detailed studies of HMC from tills can help zero in on the site of the PGE mineralization.

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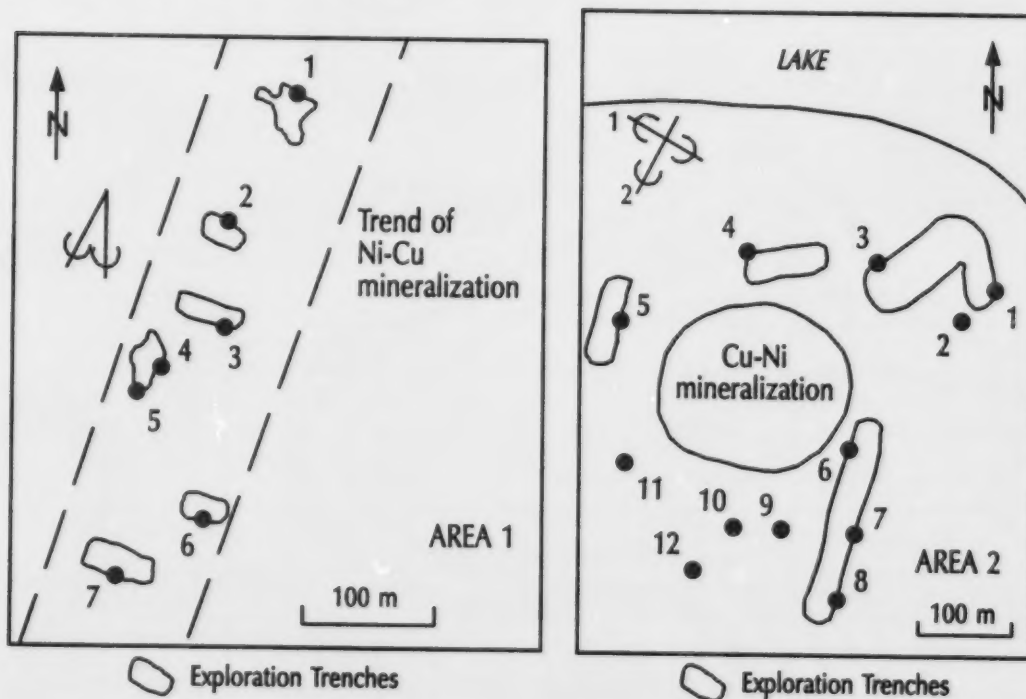


Figure 7 - Sample site location map, Areas 1 and 2, Sudbury, Ontario.

Table 4: The Distribution of Au and Pt in ashed humus and HMC's of till, and of Pd, Ni, Cu and As in ashed humus, the HMCs of till, the <2 µm fraction of B-horizon soil, and the <2 µm fraction of till, Areas 1 and 2, Sudbury, Ontario (See Figure 7 for sample locations)

SUDBURY - AREA 1

Sample Site	Au (ppb)		Pt (ppb)		Pd (ppb)			Ni (ppm)			Cu (ppm)			As (ppm)		
	Humus	Till HMC	Humus	Till HMC	Humus	Till HMC	Soil <2µm B-horizon	Humus	Till HMC	Soil <2µm B-horizon	Humus	Till HMC	Soil <2µm B-horizon	Humus	Till HMC	Soil <2µm B-horizon
1	79	139	114	4	1410	33	2	47	1855	113	99	152	4470	177	160	754
2	25	62	77	7	76	8	4	3	52	113	44	65	557	699	178	268
3	36	139	65	<2	85	109	3	7	1605	110	100	95	1600	118	215	196
4	48	10	82	17	404	58	9	17	1140	189	339	1755	2080	155	809	1843
5	67	4128	66	3	111	10	5	24	955	113	208	441	1028	155	413	1770
6	42	72	70	<2	86	5	2	2	980	108	79	103	1230	46	93	126
7	27	26	58	7	81	10	2	2	1265	123	103	119	1125	53	122	306

SUDBURY - AREA 2

Sample Site	Au (ppb)		Pt (ppb)		Pd (ppb)			Ni (ppm)			Cu (ppm)			As (ppm)		
	Humus	Till HMC	Humus	Till HMC	Humus	Till HMC	Soil <2µm B-horizon	Humus	Till HMC	Soil <2µm B-horizon	Humus	Till HMC	Soil <2µm B-horizon	Humus	Till HMC	Soil <2µm B-horizon
1	19	116	44	3	58	5	6	7	694	86	53	91	780	121	224	503
2	57	6	123	2	151	6	2	2	1785	121	51	48	2070	54	466	896
3	29	8	76	9	78	9	3	2	696	95	84	144	2160	177	1690	827
4	6	817	22	<2	14	2	2	2	351	87	91	128	377	117	617	864
5	7	19	108	<2	25	2	2	2	489	90	56	92	476	71	257	373
6	21	444	25	6	36	7	2	2	436	116	76	195	505	243	2150	430
7	12	2200	37	<2	27	4	2	8	483	77	56	65	457	98	790	703
8	2	314	8	<2	4	2	2	4	321	78	61	64	353	94	780	781
9	9	ns	12	ns	21	ns	2	ns	293	ns	27	ns	332	ns	905	ns
10	14	ns	53	ns	23	ns	2	ns	319	ns	52	ns	274	ns	174	ns
11	21	ns	44	ns	62	ns	2	ns	886	ns	69	ns	831	ns	292	ns
12	9	ns	9	ns	20	ns	2	ns	425	ns	69	ns	383	ns	292	ns

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ACKNOWLEDGEMENTS

The authors thank the management of Inco Gold, Claude Resources and Falconbridge Ltd. for permission to carry out field studies on their respective properties at Ferguson Lake, Rottenstone Lake and Sudbury, and for permission to publish this paper.

Analyses were carried out in the laboratories of Bondar-Clegg and Co. Ltd., Ottawa; Acme Analytical Laboratories Ltd., Vancouver; and the Geological Survey of Canada, Ottawa.

THE MCILVENNA BAY MASSIVE SULPHIDE DEPOSIT - A CASE HISTORY

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ABSTRACT

The Hanson Lake joint venture project and the McIlvenna Bay massive sulphide deposit are located approximately 65 km west-southwest of Flin Flon, Manitoba. Partners in the project are Cameco - A Canadian Mining & Energy Corporation (67.1% - the project operator), and Trimin Resources Inc. (32.9%).

An Aphebian sequence of felsic to mafic metavolcanics with subordinate metasedimentary rocks, which comprises part of the Hanson Lake Block, is exposed in the northernmost portion of the project area. To the south, Precambrian basement is unconformably overlain by flat-lying Paleozoic dolomites and sandstones. Regional aeromagnetic evidence, supported by drill hole data, indicates that the metavolcanic belt extends under these cover rocks. Base metal exploration in the Hanson Lake area commenced in the 1930's and resulted in the discovery of several significant occurrences and one producer, the Hanson Lake (Western Nuclear) Mine.

The Hanson Lake project was initiated in 1977 by the Saskatchewan Mining Development Corporation (now Cameco) after recognition of this area as a favourable environment for base metals. Since that time, extensive helicopter-borne and fixed wing electromagnetic and aeromagnetic surveys have been completed, followed by ground horizontal loop electromagnetic and magnetometer surveys, detailed assessment file searches, geological mapping and diamond drilling. As a result, several subeconomic base metal occurrences were discovered.

The McIlvenna Bay massive sulphide deposit was discovered beneath Paleozoic cover rocks, in March of 1988, by diamond drill testing of a moderate strength airborne/ground electromagnetic anomaly. The deposit comprises typical zoned and multi-lensoidal volcanogenic massive and stringer copper-zinc mineralization which lies conformably within a horizon of variably altered felsic metavolcanic rocks of Aphebian age. The sulphides are hosted by sericitized and chloritized dacite flows and tuffs, are overlain by alternating basalt/chert/dacite sequences and banded magnetite iron formations, and underlain by blue quartz-phyric sericite schists, sericitized rhyolites and felsic ash tuffs.

The deposit, as defined to date, consists of one main lens (Lens 2), two smaller lenses (Lenses 1 and 3) and associated stringer sulphide mineralization. The lenses strike 120° to 130°, dip 60° to 75° northeast and plunge 35° to 40° northwest. Mineralization in the massive portion of these lenses is typically rounded and oval grains of pyrite set in a finer grained matrix containing pyrite, sphalerite, minor chalcopryite and local galena, marcasite and magnetite. The estimated true thickness of the massive portion ranges from 0.5 m to 15.0 m. The stringer sulphide mineralization contains mainly chalcopryite with accessory pyrite, sphalerite and minor pyrrhotite, and ranges from less than 1 m to more than 60 m thick. The stringer sulphides, accounting for 5% to 30% of the rock by volume, are hosted by strongly chloritic and sericitic felsic metavolcanic rocks.

To date, 54 drill holes totalling 22,700 m have tested the deposit, which remains open at depth and along strike to the northwest.

INTRODUCTION

The McIlvenna Bay copper-zinc, volcanogenic, massive sulphide deposit is located approximately 1 km south of Hanson Lake, Saskatchewan, and 65 km west-southwest of Flin Flon, Manitoba (Figure 1). The deposit was discovered in March of 1988 following an integrated program of geological area selection and helicopter-borne electromagnetic (INPUT) surveys, ground geophysical surveys (HLEM/mag), and diamond drilling.

At the time of the discovery, partners in the Hanson Lake joint venture included the Saskatchewan Mining Development Corporation - SMDC (now Cameco), Esso Minerals Canada, and Tri-Gold Industries (now Trimin Resources Incorporated). Partners currently involved in the joint venture are Cameco (67.1% - project operator) and Trimin (32.9%).

The objective of this paper is to provide a summary of exploration history in the Hanson Lake area, and an overview of the geological and geophysical characteristics of the McIlvenna Bay deposit.

REGIONAL GEOLOGY

All Precambrian supracrustal rocks in the Hanson Lake area are Archean in age, based on a U-Pb zircon age of 1888 ± 12 Ma for felsic metavolcanics (Van Schmus *et al.*, 1987). The supracrustals comprise conformable metasedimentary and metavolcanic strata and their gneissic equivalents. They have been folded and intruded by syntectonic granodiorite and subsequent post-tectonic diorite and gabbro (Byers, 1957; Coleman *et al.*, 1970). The entire supracrustal/intrusive package forms part of the Hanson Lake Block (Figure 1).

Recognizable volcanic rocks underlie most of the western part of Hanson Lake. They consist of massive and fragmental flows of rhyolitic to basaltic composition with interbedded tuffs, and coarse fragmental rocks, as well as volcanoclastic and exhalative sediments. These rocks are considered to be the equivalent of the Amisk Group in the Flin Flon area, which hosts several important base metal mines including Trout Lake and the world class Flin Flon Mine.

At least two cycles of felsic volcanic rocks are exposed at Hanson Lake with each cycle possessing a mineralized exhalative terminal phase (Figure 2). The lower cycle rocks are monotonous grey, fine-grained, poorly layered dacite to rhyolite flows and fragmentals.

The upper cycle rocks are rhyolitic in composition, generally blue quartz- and feldspar-phyric flows, flow breccias, debris flows and coarse fragmentals. They are intruded by subvolcanic quartz-feldspar porphyry which forms the core of a rhyolite dome. The McIlvenna Bay deposit is stratigraphically located near the top of a similar felsic dome. A more detailed discussion of the geology of exposed Precambrian felsic rocks around the historic Hanson Lake Mine is presented by Sibbald (1989).

Metasedimentary rocks structurally overlying the volcanic sequence are located in the central and eastern part of Hanson Lake. The metasedimentary sequence is dominated by greywackes with some interbedded argillite and conglomerate. These rocks and the metavolcanics are intruded by large masses of syntectonic granodiorite and quartz diorite to the north and east, and by a major post-tectonic diorite and gabbro body to the east and south (Figure 2). The supracrustal rocks have been deformed by at least two major folding events (Byers, 1957) and are cut by two major fault sets (Coleman *et al.*, 1970). Early isoclinal folds (F1) have been refolded by north-trending, open to tight, doubly plunging upright folds (F2) (Macdonald, 1975). The Jackpine Lake anticline, located to the west of Hanson Lake, is an example of the F2 structure.

To the south and southwest, the Precambrian rocks are covered by flat-lying Ordovician dolomites and basal sandstones. The McIlvenna Bay massive sulphide deposit lies just south of the Precambrian-Paleozoic unconformity edge.

A northerly-trending fault zone, located 1 km west of Bertrum Bay on Hanson Lake, has been correlated with the Tabbernor Fault (Coleman, 1970). A second fault set trends in a north-northeasterly direction.

Metamorphic grade, which is generally upper greenschist to lower amphibolite facies in the south Hanson Lake area, increases to the north and west to upper amphibolite.

EXPLORATION HISTORY

The first known prospecting in the Hanson Lake area was carried out during the 1930's. Prior to 1952, two base metal prospects, the Young lead-zinc showing and the Bluebird Island copper showing, were discovered and drill tested (Figure 3). Extensive exploration work, including airborne and ground electromagnetic surveys and diamond drilling, was subsequently carried out by Hudson Bay Exploration and Development Company (H.B.E.D.) between 1952 and 1956. This work resulted in the discovery of the South Bay showing; a series of small lenses of massive and stringer sulphide mineralization occurring over a min-

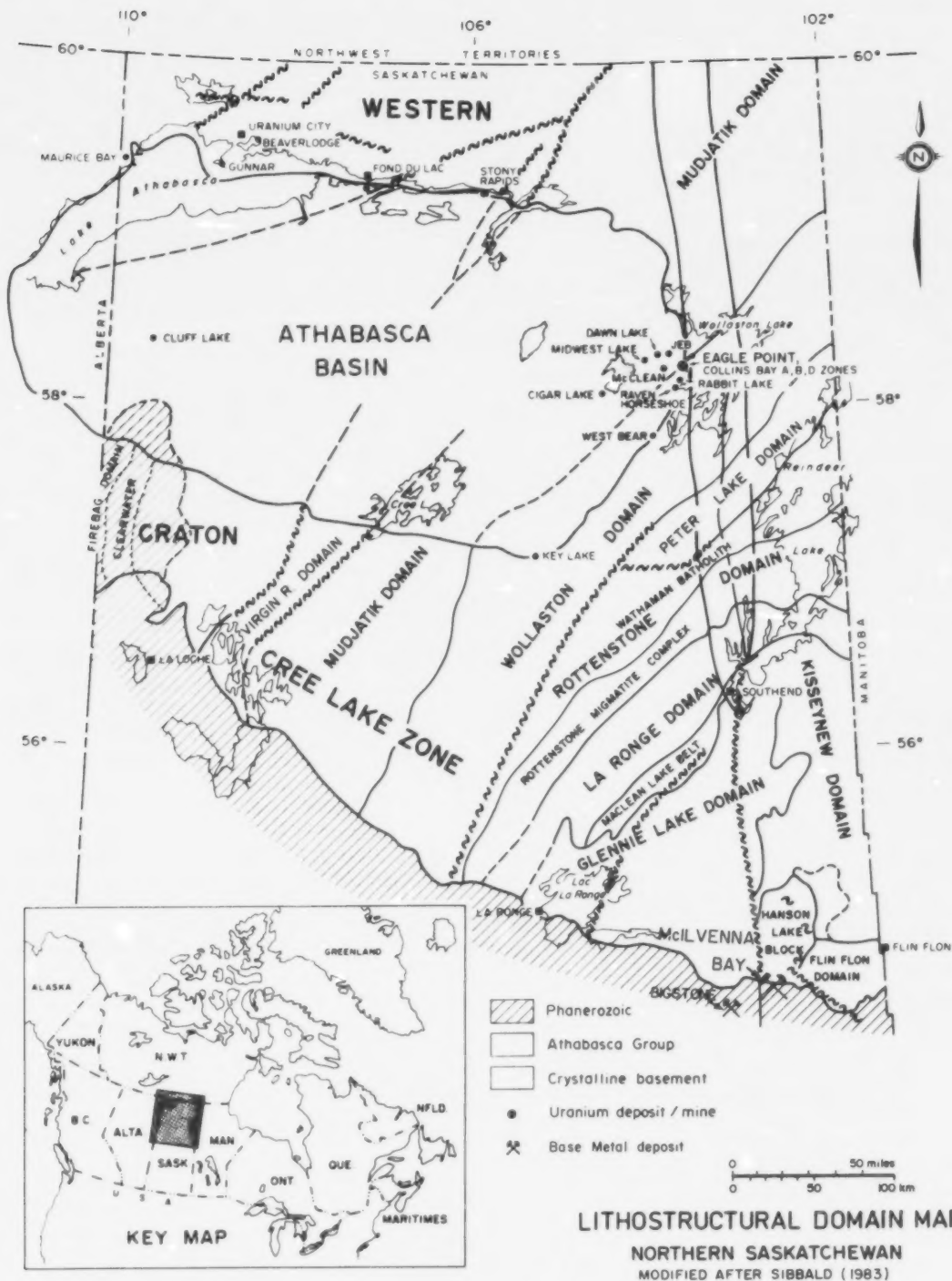


Figure 1 - Lithostructural domain map of northern Saskatchewan with locations of the McIlvenna Bay and Bigstone massive sulphide deposits (in southeast corner of figure) (after Sibbald, 1983).

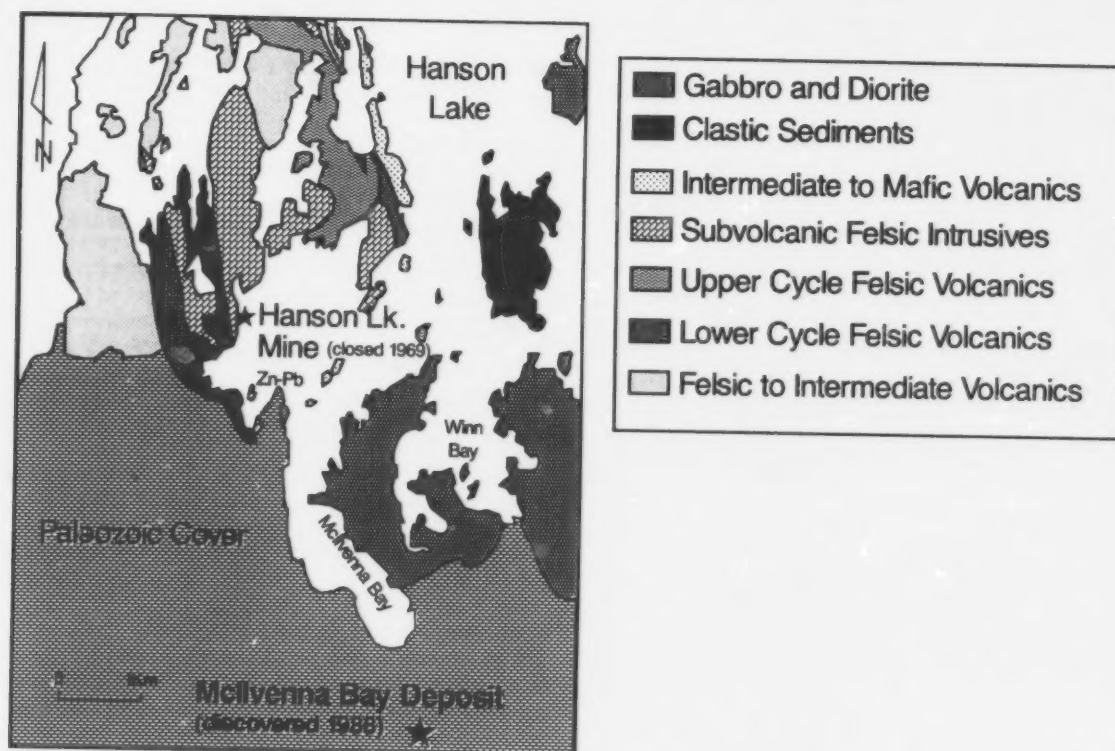


Figure 2 - Geology of the Hanson Lake area, west sheet. (After Koziol et al., 1984.)

imum strike length of 900 m and to a depth of 200 m (Figure 3). The mineralization at South Bay is hosted by a weak shear zone at the contact between a dacitic flow sequence and quartz porphyritic rhyolite and dacite (Beck, 1959; Koziol, 1985). One of the better 1954 H.B.E.D. holes yielded intersections of over 20 m grading 0.2% Cu and 1.1% Zn (H.B.E.D., 1954).

In 1954, Mr. A. Ramsay, a Flin Flon prospector, discovered a chalcopyrite-bornite-sphalerite-bearing shear zone in a biotite-microcline-garnet gneiss along the east shore of Little Keputch Lake, located approximately 1 km north of Botham Bay (Figure 3). Diamond drilling programs between 1954 and 1970 indicated that the zone has an approximate strike length of 300 m and is open at depth below 300 m (Beck, 1959). The Ramsay deposit is estimated to contain mineral reserves of 738,500 t of 2.1% Cu, 1.8% Zn, 7.9 g/t Ag and 0.1 g/t Au to 330 m depth (Canadian Mines Handbook 1989-90).

In 1957, the Parrex Mining syndicate drilled 12 holes to investigate a zone of Zn-Pb mineralization beneath Hanson Lake which ultimately became the Hanson Lake Mine (Figure 3). The mine, operated by Western Nuclear Mines between 1967 and 1969, produced 147,000 t containing 10% Zn, 5.8% Pb, 0.5% Cu and 137.0 g/t Ag.

In the early 1980's, exploration by the Granges-SMDC Bigstone joint venture resulted in the discovery of the Bigstone deposit, located approximately 25 km southwest of Hanson Lake (Figure 1). The deposit consists of both stringer and massive sulphides hosted by felsic metavolcanic rocks. Mineral reserves have been estimated at 3,580,000 t averaging 1.87% Cu, 1.1% Zn, 9.9 g/t Ag and 0.4 g/t Au (Granges Exploration Ltd., 1984).

In 1985, the Granges-Troymin Balsam Lake joint venture announced the discovery of massive sulphides under Paleozoic cover rocks at McDermott Lake (Figure 3). The mineralization occurs within altered felsic metavolcanic rocks. The best mineralized drill hole was reported to contain 3.37% Zn, 3.29% Cu, 52.45 g/t Ag, 3.6 g/t Au over a 6.5 m core length (Troymin Resources, 1986).

SMDC (now Cameco) first acquired claims in the Hanson Lake area in 1976. In 1977, an Aerodot helicopter-borne, combined electromagnetic/magnetic survey was flown (single frequency, vertical coaxial coil configuration). Detailed assessment file searches and geological mapping of exposed basement were undertaken between 1977 and 1986. Selected HEM responses were followed up by horizontal loop electromagnetic and magnetic surveys and subsequent diamond drilling (70 drill holes

totalling 11,900 m). Several subeconomic base metal prospects were discovered, including the Miskat, Grid B and Zinc Zone (Figure 3).

The Miskat Zone is a metavolcanic hosted, massive sulphide deposit which contains approximately

500,000 t of 0.5% Cu and 0.5% Zn (Koziol and Fox, 1979; Koziol and Neale, 1981).

The Grid B showing consists of disseminated pyrite and sphalerite mineralization hosted in a chlorite schist fault zone (Gay and Koch, 1982; Kreczmer and Koch, 1983; Koziol *et al.*, 1984). This zone was traced

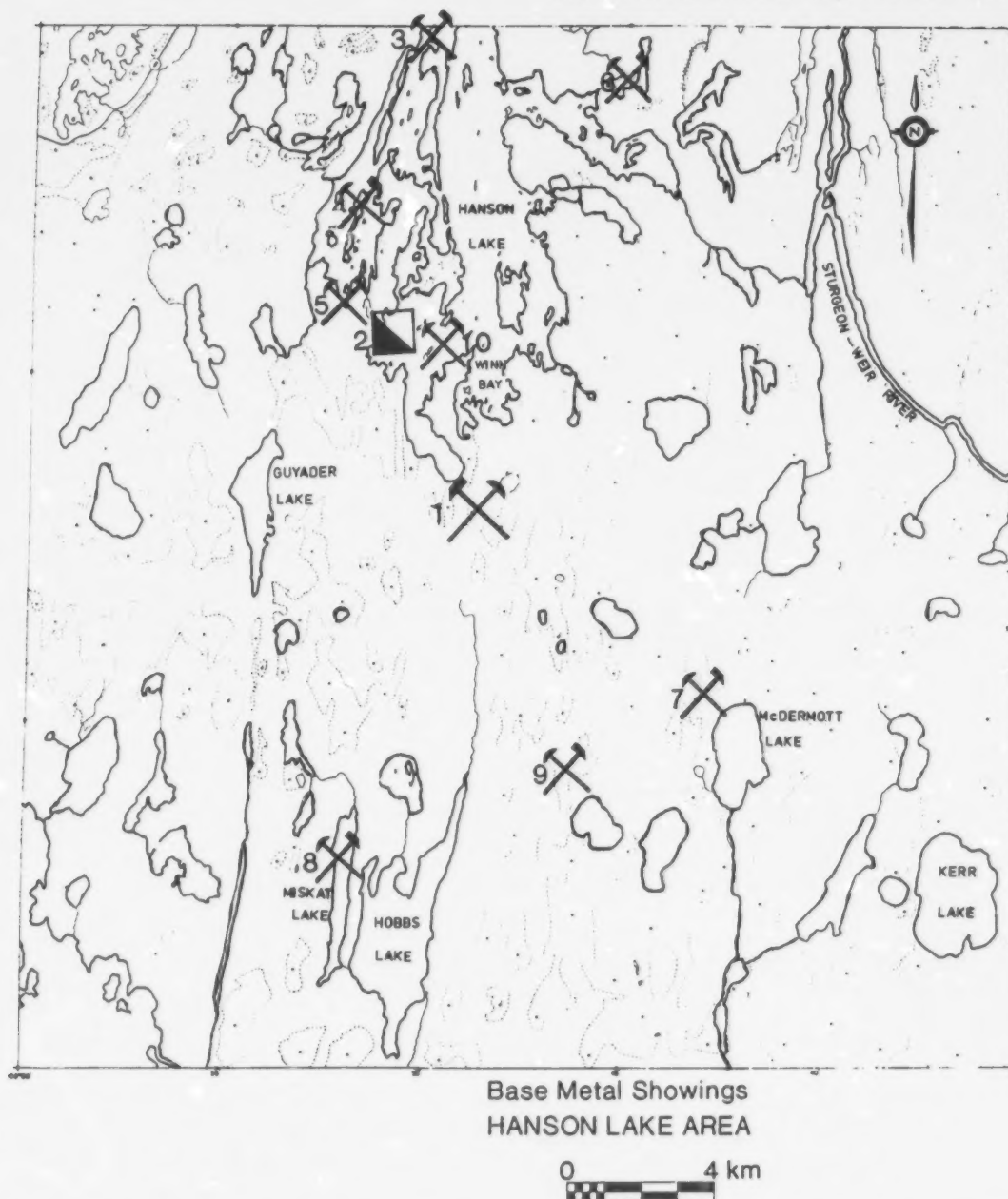


Figure 3 - Base metal deposits in the Hanson Lake area with locations of (1) the McIlvenna Bay deposit, (2) the Hanson Lake Mine, (3) the Young showing, (4) the Bluebird Island showing, (5) the South Bay showing, (6) the Ramsay deposit, (7) the McDermott Lake "Balsam" showing, (8) the Miskat zone, (9) the Grid B showing, and (10) the Zinc Zone showing.

over a 120 m strike length and drill tested to 230 m depth with assays of up to 3.6% Zn over 1.5 m core lengths.

The Zinc Zone showing, discovered in 1984, is a massive sulphide occurrence hosted within a sequence of intermediate volcanics, chert, tuffs, argillite and banded magnetite-chert iron formation beneath Hanson Lake (Koziol *et al.*, 1984; Koziol, 1985, 1986). The best drill hole intersection obtained from the Zinc Zone was a 1.5 m core length containing 30.7% Zn, 0.8% Pb and 178.3 g/t Ag with only minor copper and gold.

DEPOSIT DISCOVERY

The announcement of massive sulphide mineralization at McDermott Lake coupled with the favourable geology exposed at Hanson Lake prompted the Hanson Lake joint venture to re-fly portions of the project area. A Barringer/Questor Mark VI helicopter INPUT survey was flown in January 1986. Two flight line orientations were chosen to accommodate a local change in regional aeromagnetic trend, which was recognized south of McIlvenna Bay (Figures 4 and 5).

The INPUT survey outlined what appeared to be a formational conductor trending roughly 090° to 120°, flanking a linear aeromagnetic high having similar orientation (Figure 5). The anomaly is a 4-6 channel INPUT conductor with approximately 1200 m strike length, characterized by an estimated conductivity-thickness product ranging between 8-10 siemens (S), east-southeast of FL 20140N (Figures 5 and 6), and 20-50S, to the west-northwest. Depth estimates were determined by Questor to fall within the 40-100 m range (below surface), with a dip of 65° to 70° to the northeast (Martyn, 1986).

Ground follow-up of the 1986 McIlvenna Bay INPUT anomaly was completed in January, 1988, when the area was covered by ground magnetometer and horizontal loop electromagnetic (HLEM) surveys (Figures 7 and 8, respectively). The interpreted HLEM conductor axis associated with the McIlvenna Bay deposit (Figure 8) has a strike length in excess of 800 m, and is characterized by moderate conductance (5-11S). The depth of the conductor was estimated at 40 m to 90 m (plunging to the northwest), and dipping 60° to 85° to the northeast (after Nair *et al.*, 1968).

A six hole diamond drill program was then carried out to test the HLEM conductor. The first hole intersected a 24 m copper stringer zone, within which was a 1 m wide massive sulphide section. The other five drill holes also intersected stringer and massive mineralization including hole HA-06, which cut 5.0 m

of 3.3% Cu, 9.6% Zn, 79.9 g/t Ag and 1.02 g/t Au. An additional 48 drill holes were completed during the latter part of 1988 and 1989. Subsequent geophysical work included HLEM and borehole Pulse EM.

DEPOSIT GEOLOGY

The McIlvenna Bay massive sulphide mineralization is a structurally deformed, volcanogenic copper-zinc sulphide deposit which lies conformably within a horizon of altered felsic metavolcanic rocks (Koziol *et al.*, 1989). The deposit occurs within the following generalized stratigraphic succession (Figures 9, 10 and 11) (from youngest to oldest):

Post-Tectonic Intrusive Rocks

- Gabbro and mafic dykes

Hanging Wall Sequence

- Mixed metavolcanic rocks
- Banded magnetite-pyrrhotite-bearing iron formation (present locally)
- Mafic metavolcanics
- Banded magnetite-bearing iron formation
- Iron formation fault
- Mixed mafic and felsic metavolcanics

Host Sequence

- massive sulphide mineralization (Lens 1 and Lens 3)
- Dacite and dacitic tuff
- Massive sulphide mineralization (Lens 2)

Footwall Sequence

- Quartz-sericite and chlorite schists
- Bedded rhyolite (chert?), felsic tuff and ash tuff

Post-Tectonic Intrusive Rocks

Gabbro and Mafic Dykes

Post-tectonic intrusions include sill-like bodies of coarse-grained, grey green, amphibole metagabbro. The metagabbro appears to be unaltered and is most abundant in the hanging wall sequence on the southeast side of the deposit where thicknesses exceed 100 m. Thin (a few centimetres to 2 m), fine-grained mafic dykes are common in the footwall, massive sulphide lenses, and sulphide stringer zone.

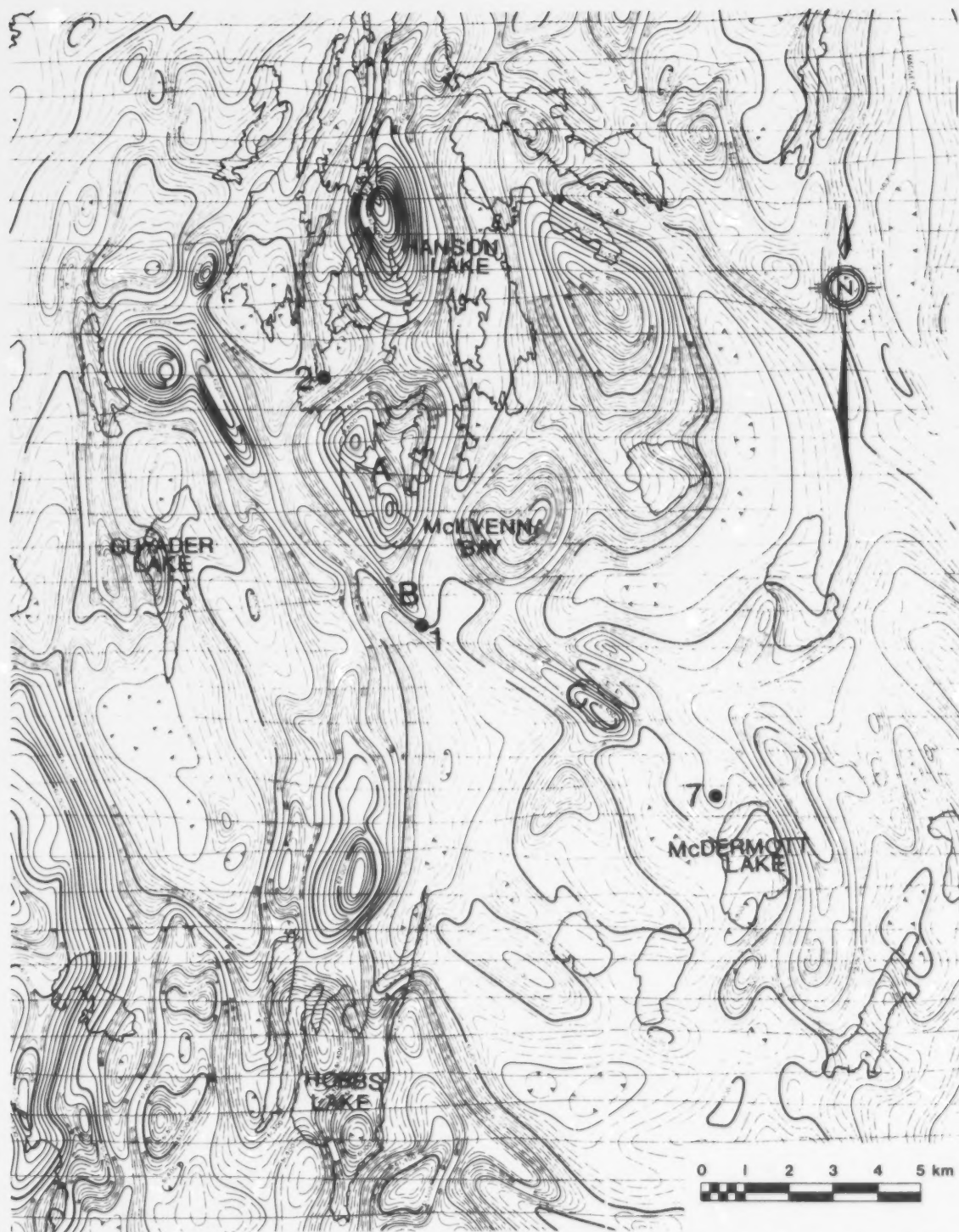


Figure 4 - Regional total field aeromagnetic map of the Hanson Lake area with locations of (1) the McIlvenna Bay deposit, (2) the Hanson Lake Mine, and (7) the McDermott Lake 'Balsam' showing. The McIlvenna Bay deposit occurs at the southern tip of regional aeromagnetic anomaly A, which correlates with a large, gabbro/diorite intrusive mapped in the area by Byers (1957); refer to Figure 2. Based on total field aeromagnetic interpretation, the intrusion extends south of McIlvenna Bay, where it appears to pinch out under Paleozoic cover (B) (after GSC Aeromagnetic Series Map Sheet 63 L/10, Geophysics Paper 4605).

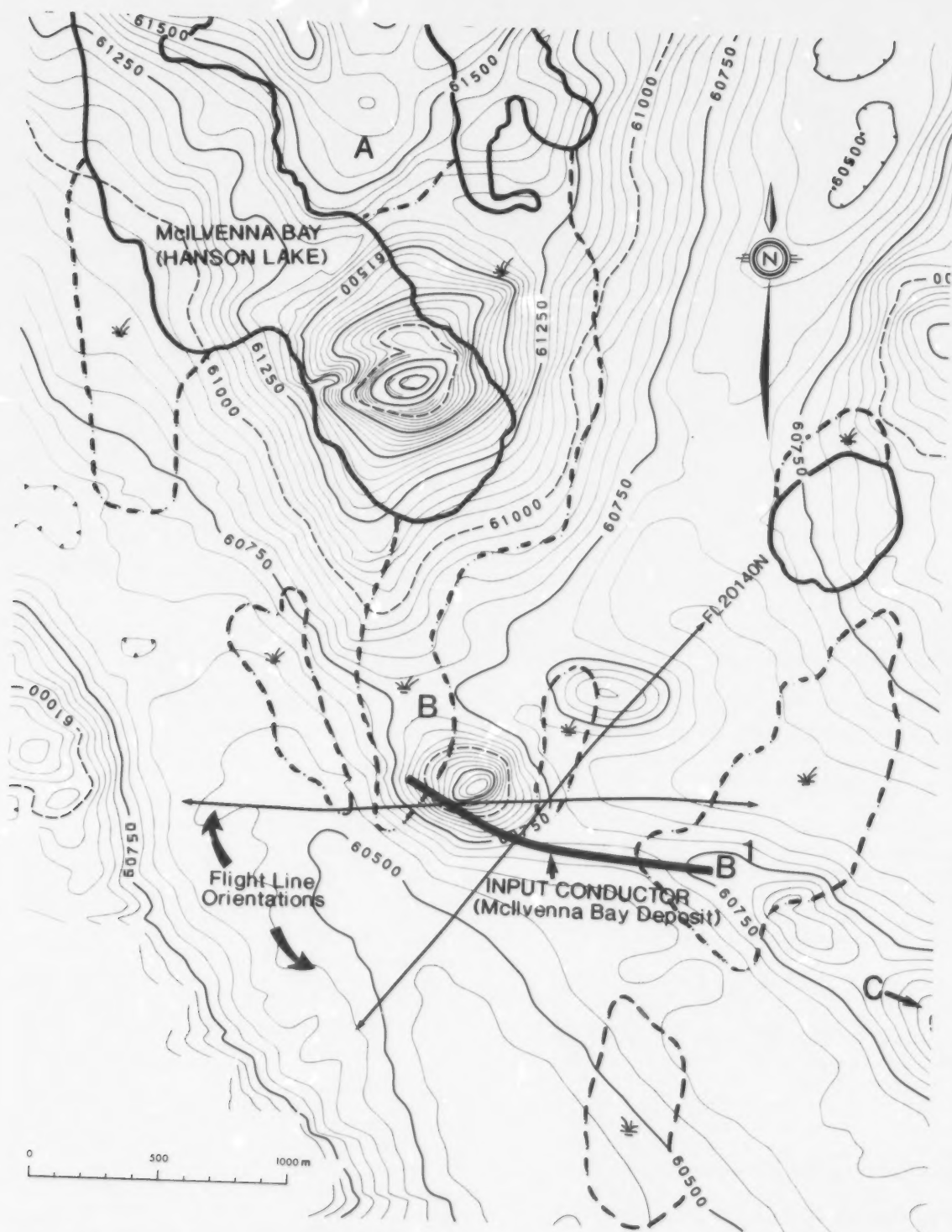


Figure 5 - 1986 total field aeromagnetic map of the McIlvenna Bay area, Hanson Lake, with locations of regional aeromagnetic anomalies A, B, and C (refer to Figure 4), INPUT conductor axis and flight line orientations over the McIlvenna Bay deposit.

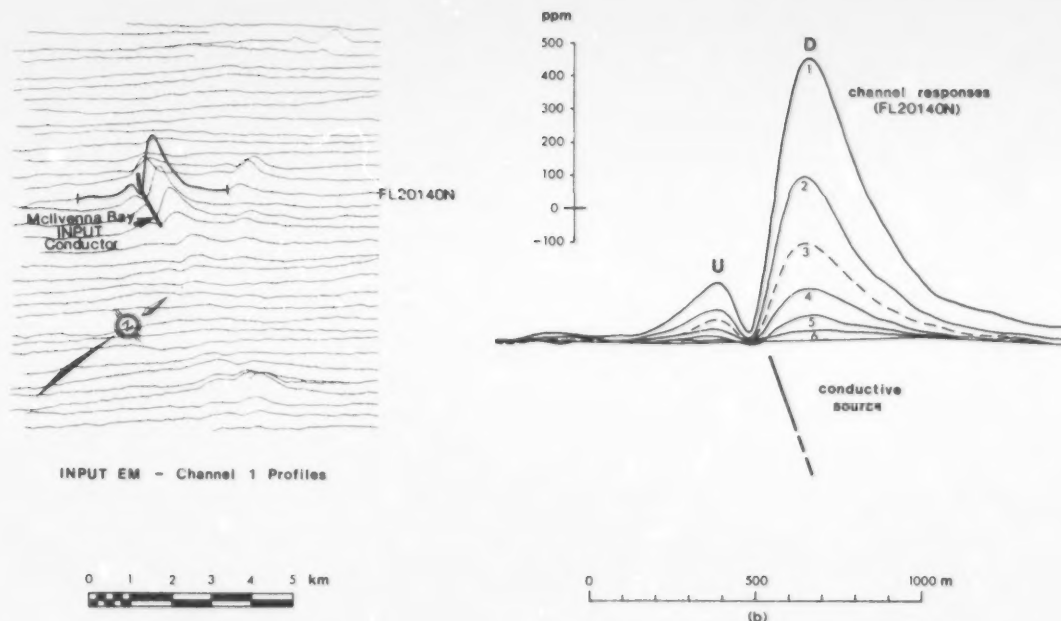


Figure 6 - a) INPUT EM profile map (channel 1 amplitudes; 2 ms pulse width) with location of 1986 INPUT conductor axis over the McIlvanna Bay deposit. b) Stacked INPUT EM profiles (channels 1 through 6, FL 20140N) over the McIlvanna Bay deposit. The profiles display a 'classic' thin-sheet INPUT response for a moderately dipping conductor of intermediate conductance buried within 50 m of surface. Sense of dip is indicated by the asymmetric, up-dip (U) and down-dip (D) response peaks. The flight line segment shown here coincides roughly with drill section 9750E (Figure 11), although at a slightly different orientation.

Hanging Wall Sequence

Mixed Metavolcanic Rocks

The thickness of this unit is not known. It encompasses all lithologies above the uppermost iron formation. Dominant rock types include mafic and intermediate tuffs and flows with a greater proportion of felsic tuffs and volcanoclastic sediments higher in the section. Approximately 100 m from the base, a dacitic tuff sequence hosts vein and semi-massive sphalerite-pyrite mineralization, suggesting distal sulphide mineralization along this stratigraphic horizon.

Banded Magnetite-Pyrrhotite Bearing Iron Formation

The iron formation is from 1 m to 15 m thick and lies within or immediately above the massive mafic metavolcanics (Figure 10). It is found only over the western half of the deposit (Figure 9) and is very similar to the lower iron formation. In addition to the magnetite, stringers, wisps and semi-massive to massive bands of pyrrhotite are also present.

Mafic Metavolcanics

Mafic metavolcanics, ranging from 50 to 120 m thick, comprise a monotonous sequence of fine-grained, dark green massive basalt flows. In places, they are

strongly carbonate and carbonate-epidote altered. Near the base, some foliation (bedding?) is observed, possibly indicating a mafic tuff component.

Banded Magnetite-Bearing Iron Formation

This iron formation unit, which ranges from 1 to 10 m thick, consists of beds of magnetite alternating with chert and garnet-chlorite-epidote-carbonate rock. Individual beds range from 1 mm to several centimetres thick, with an average of 1 cm. Magnetite occurs as euhedral, generally fine-grained crystals comprising 20% to 40% of the iron formation. Garnet porphyroblasts in the garnet-chlorite-epidote rich bands range from mm to 1 cm in diameter and make up from 15% to 70% of these bands. Kink and soft sediment folding are prominent in the iron formation.

Iron Formation Fault

The fault zone is 1 to 10 m thick and occurs at or near the base of the lower iron formation. It is characterized by a graphite-carbonate gouge or by graphite coated, chloritized, strongly brecciated country rock. The fault, which can be traced along the entire length of the deposit, can be used together with the overlying iron formation as a regional marker for future exploration.

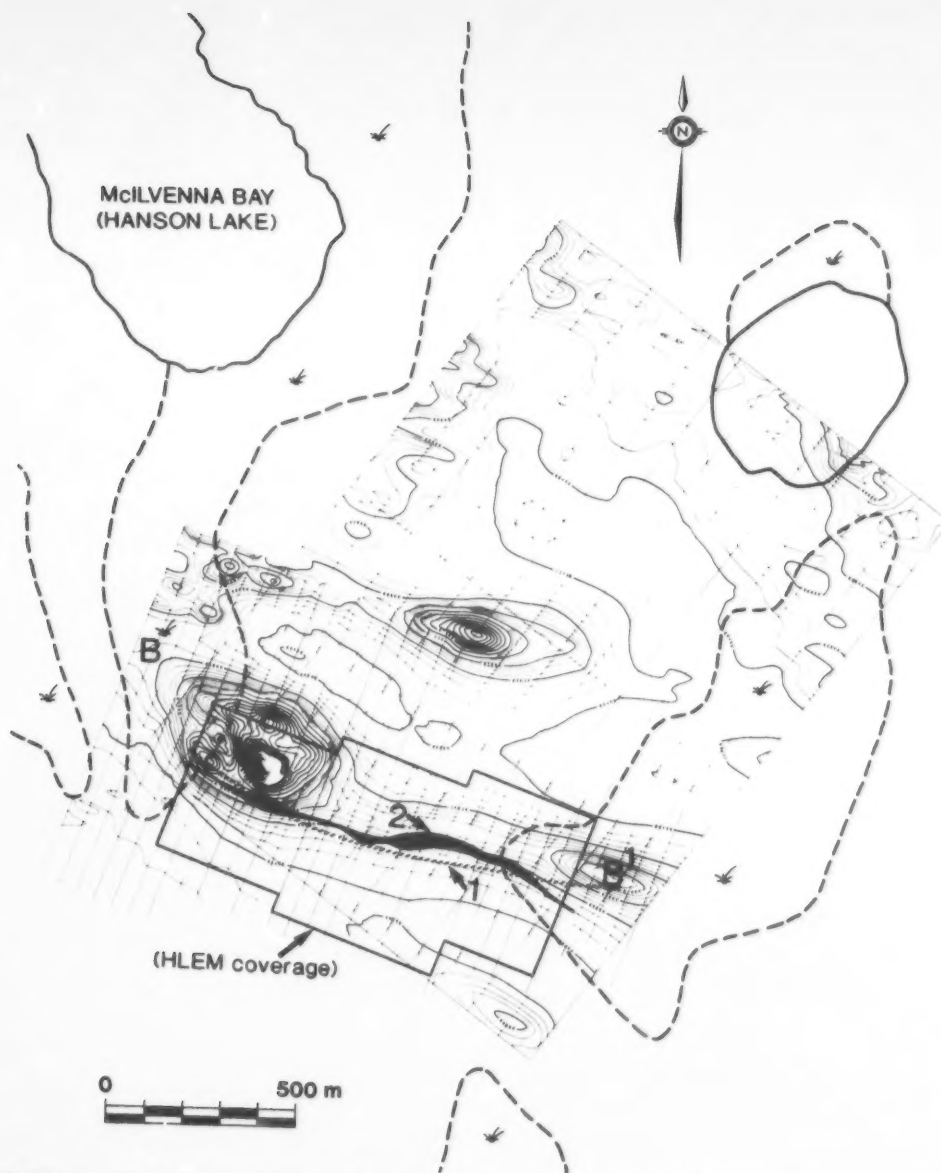


Figure 7 - Total field magnetic map over the McIlvenna Bay deposit with locations of (1) the interpreted INPUT conductor axis, and (2) the 1988 HLEM conductor axis. The axis of magnetic anomaly B-B', offset slightly to the north of the conductor(s), was originally thought to represent the southern extension of a regional gabbro/diorite intrusive (A-B, Figures 4 and 5). Drill core from the area suggests, however, that anomaly B-B' originates from two or more banded magnetite/pyrrhotite - chert iron formations in the hanging wall sequence of the McIlvenna Bay deposit (Figures 9, 10, and 11). The area outlined in the figure represents the extent of HLEM coverage shown in Figure 8.

Mixed Mafic and Felsic Metavolcanics

This 40 to 90 m thick unit is a mixed package of alternating basalt flows, felsic and mafic tuff beds, dacite flows and chert interbeds. The mafic metavolcanics comprise from 50% to 70%, with individual flows up to 20 m thick. The felsic metavolcanic component increases towards the base. Chert beds locally exceed 20 m in thickness.

Host Sequence

The massive sulphide mineralization of Lenses 1, 2, and 3 are described in a later section.

Dacite and Dacitic Tuff

Massive dacite and dacitic tuff with sporadic cherty interbeds can be found up to 40 m thick and occur along the entire length of the deposit. Massive and

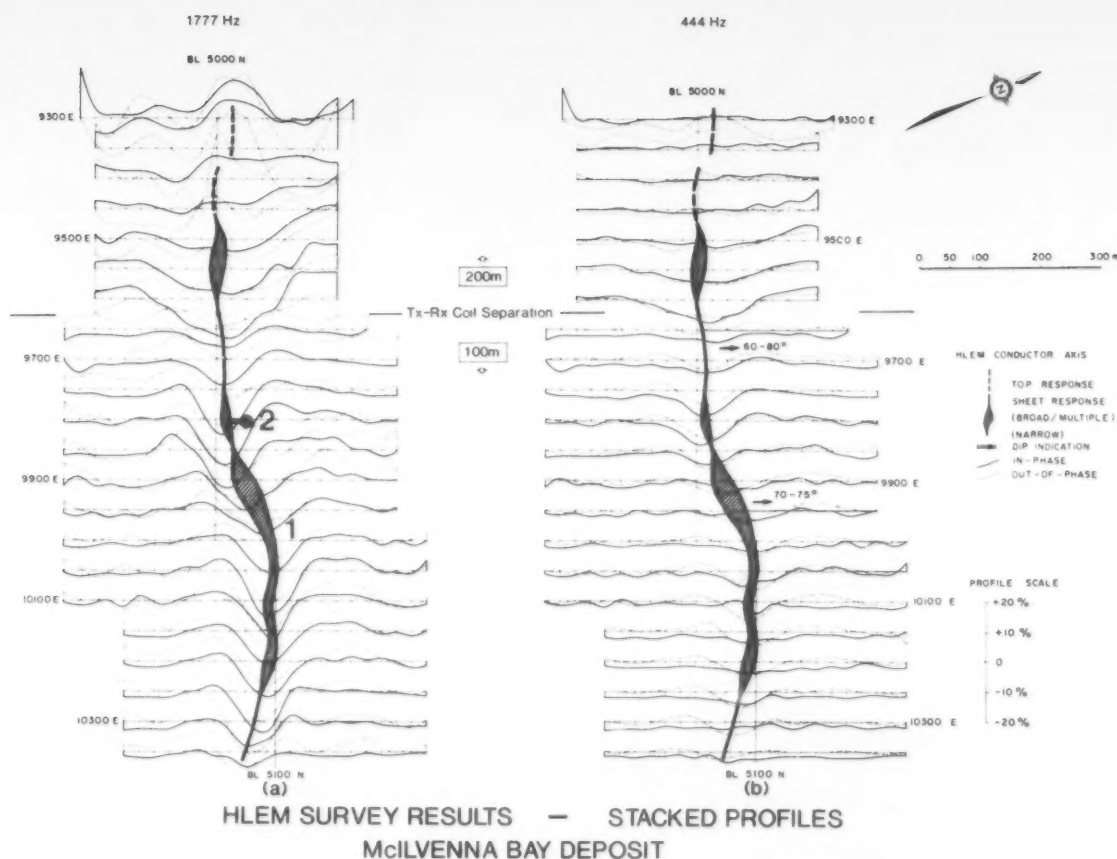


Figure 8 - Stacked HLEM profile map over the McIlvenna Bay deposit with locations of (1) interpreted 1988 HLEM conductor axis, and (2) 'discovery' hole. Figure 8a represents the 1777 Hz response profiles (100 and 200 m coil separations; Apex Max Min II + EM system); Figure 8b represents the 444 Hz responses. Re-evaluation of the HLEM data together with diamond drill information suggests that the HLEM responses undergo a transition along strike (from 'thin-sheet' conductive responses east of line 9550E, to interpreted 'top' responses west of line 9400E). The change in response character is likely due to the zone's westwardly plunge (refer to Figure 12).

stringer mineralization are found near the stratigraphic top (Lenses 1 and 3) and at the base (Lens 2) of this unit. The dacite and tuff are variably altered. Alteration minerals include sericite, carbonate, chlorite, biotite and andalusite. Andalusite is present in minor amounts throughout, but is most evident in proximity to the chlorite schist as euhedral to subhedral crystals up to 0.8 cm in length comprising from 1 to 15% of the rock.

Footwall Sequence

Quartz - Sericite and Chlorite Schists

Quartz-sericite and chlorite schists range from only a few metres in the southeast to greater than 100 m thickness near the centre and northwest portions of the deposit. The unit forms the altered footwall adjacent to the massive sulphides, grading laterally from blue quartz eye-bearing sericite schist in the

southeast to chlorite-sericite and chlorite-talc schist near the centre and northwest portion of the deposit. Copper stringer mineralization is hosted by this unit and is typically localized within chloritic schists, but is also found in the sericite schist. Magnetite occurs in the chlorite schist in the northwest part of deposit as subhedral porphyroblasts up to 2 mm in size.

The chlorite and chlorite-talc schists are interpreted as hydrothermally altered 'vent' rocks that have been transposed by later structural deformation into semi-concordance with the massive sulphide lenses.

Bedded Rhyolite (Chert?), Felsic Tuff and Ash Tuff

The true thickness of this unit is not known but it is greater than 70 m at the east end of the deposit. The unit comprises alternating sections of massive cream to buff rhyolite and finely banded siliceous rhyolite. The latter shows very fine partings of sericite and an

-100m Plan

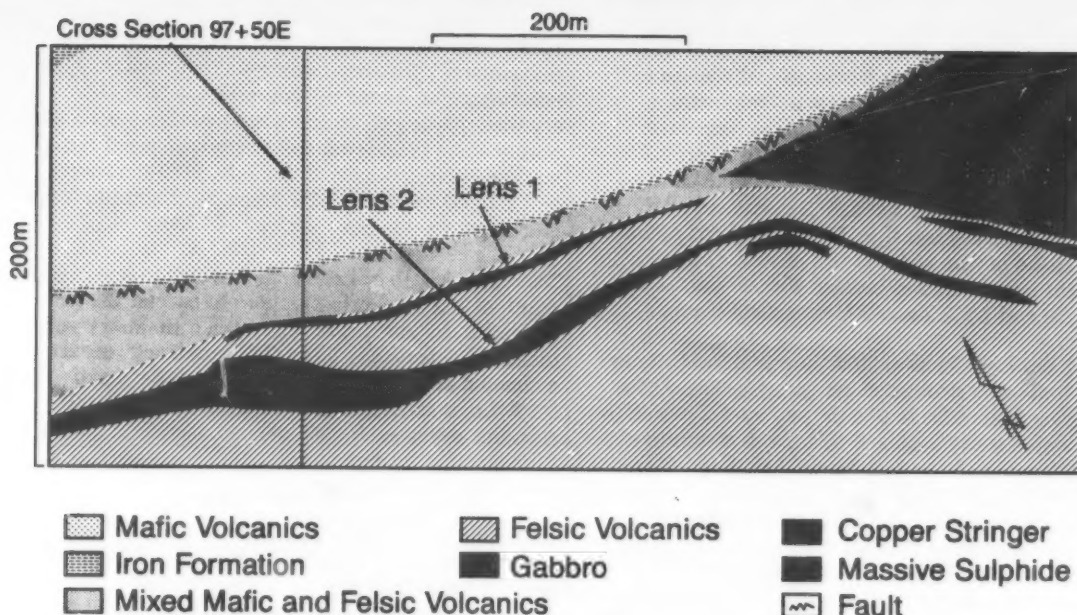


Figure 9 - 100 m level plan for the McIlvenna Bay deposit showing the geology of Lenses 1, 2, and 3.

apple green mineral, possibly chlorite and/or fuchsite. The siliceous rhyolite sections are quartz phyric in places and range from several centimetres to several metres thick. Fine- to coarse-bedded felsic tuffs and felsic ash beds are also present.

Mineralization

The McIlvenna Bay deposit, as defined to date, consists of one main lens (Lens 2) and two satellite lenses (Lenses 1 and 3) (Figure 9). These stratabound lenses of massive sulphides are hosted by felsic metavolcanic rocks which strike approximately 120° to 130° , dip 60° to 75° northeast, and plunge 35° to 45° to the northwest. They are underlain by zones of stringer sulphide mineralization.

The copper-zinc massive sulphide mineralization is typically composed of subhedral, rounded to oval pyrite grains ranging from 0.3 mm to 2.0 mm in diameter, set in a finer-grained matrix of sphalerite, pyrite and carbonate-silicate gangue. Sphalerite content commonly ranges from 10% to 20%, but locally may be as high as 50%. Chalcopyrite, commonly < 1% but as high as 10% by volume, is generally intergrown with sphalerite.

Galena occurs as fine-grained disseminations within the massive sulphide. More significant concentrations of coarse-grained galena are locally associated with a

carbonate-silicate matrix. Minor pyrrhotite, ilmenite/magnetite, marcasite and arsenopyrite are disseminated in the massive sulphide zone. The principal gangue minerals are carbonate, chlorite, actinolite and quartz.

The copper stringer sulphide mineralization is typically composed of irregular chalcopyrite and pyrite aggregates, stringers and veins hosted in a chlorite-sericite-quartz $\pm$ carbonate matrix. The stringer zone ranges from less than 1 m to greater than 60 m thick. Copper content of the stringer zone is generally 1% to 2%, but with sections carrying higher values. Pyrrhotite locally replaces pyrite as the secondary sulphide mineral, and gold mineralization is elevated proportionately (values up to 4.1 g/t over 3.7 m). Minor constituents are disseminated sphalerite, galena, arsenopyrite, ilmenite/magnetite and marcasite. The principal gangue minerals are chlorite, sericite and quartz.

Magnetite is a significant component of the massive and stringer sulphide mineralization, particularly in the central and western portions of Lens 2. It occurs locally as fine to coarse disseminated euhedral to subhedral crystals and bands in the massive sulphides and as finely disseminated crystals in the stringer and underlying chlorite alteration zones.

Lens 1 lies near the upper contact between the host dacite/dacitic tuff unit and the hanging wall sequence and persists to 900 m vertical depth. Mineralization in this lens consists of a copper stringer zone near the Paleozoic-Precambrian unconformity in the extreme northwest and massive pyrite-sphalerite towards the southeast. The lens has an estimated strike length of 300 m and is present to a vertical depth of 900 m. The lens averages 3.3 m thick at depths shallower than 300 m, but decreases with depth to generally less than 1 m thick, then increases again to 2.4 m true width at 900 m vertical depth. The lens is estimated to contain 400,000 tonnes of 1.7% Cu and 2.5% Zn to 300 m vertical depth.

Lens 2 lies from 10 m to 20 m stratigraphically below Lens 1, above a strong sericite and chlorite-sericite alteration zone. This lens is the largest discovered to date, with a strike length of 600 m and a vertical continuity from the Paleozoic-Precambrian unconformity to below 900 m vertical depth (Figure 12). The massive sulphide portion of Lens 2 ranges from less than 1 m to greater than 15 m thick (Figures 10, 11 and 12) and, at present, has the greatest potential for forming a commercially viable deposit. Lens 2 is open down plunge and along strike to the northwest.

A well-developed metal zoning exists in Lens 2. A copper dominant stringer zone in the northwest passes into zinc-copper-gold-silver±lead massive sulphides near the centre and this, in turn, into a zinc-rich massive pyrite zone in the southeast. 'Keel' type mineralization, identified as semi-massive chalcopyrite-pyrite and chalcopyrite-pyrrhotite breccia, occurs along the central and western edges of the massive portion of Lens 2. To July, 1989 a resource of 7,100,000 tonnes of 1.1% Cu, 6.5% Zn, 0.54 g/t Au and 28 g/t Ag was estimated for this lens.

The strike length of Lens 3, intersected to a vertical depth of 200 m, does not appear to exceed 150 m (Koziol *et al.*, 1989). The maximum estimated true thickness observed is 1.7 m. The contained resource, estimated at 40,000 tonnes grading 1.6% Cu and 8.1% Zn, is small and is not included in the total resource estimates for the deposit.

Alteration

Extensive, structurally modified alteration zones have been noted beneath the lenses. They have been flattened parallel to the strike of the regional northwesterly foliation. They are characterized by dark green chlorite, chlorite-talc and siliceous schists near the centre and at the northwestern end of the

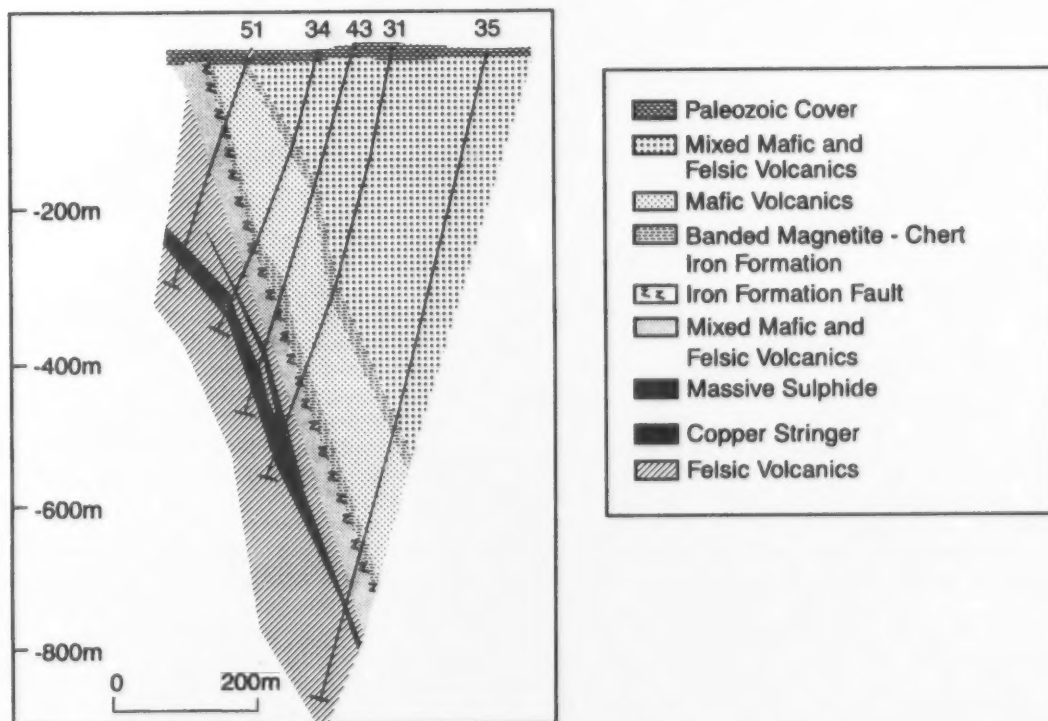


Figure 10 - Cross section 93+50 E looking 298° (McIlwenna Bay deposit).

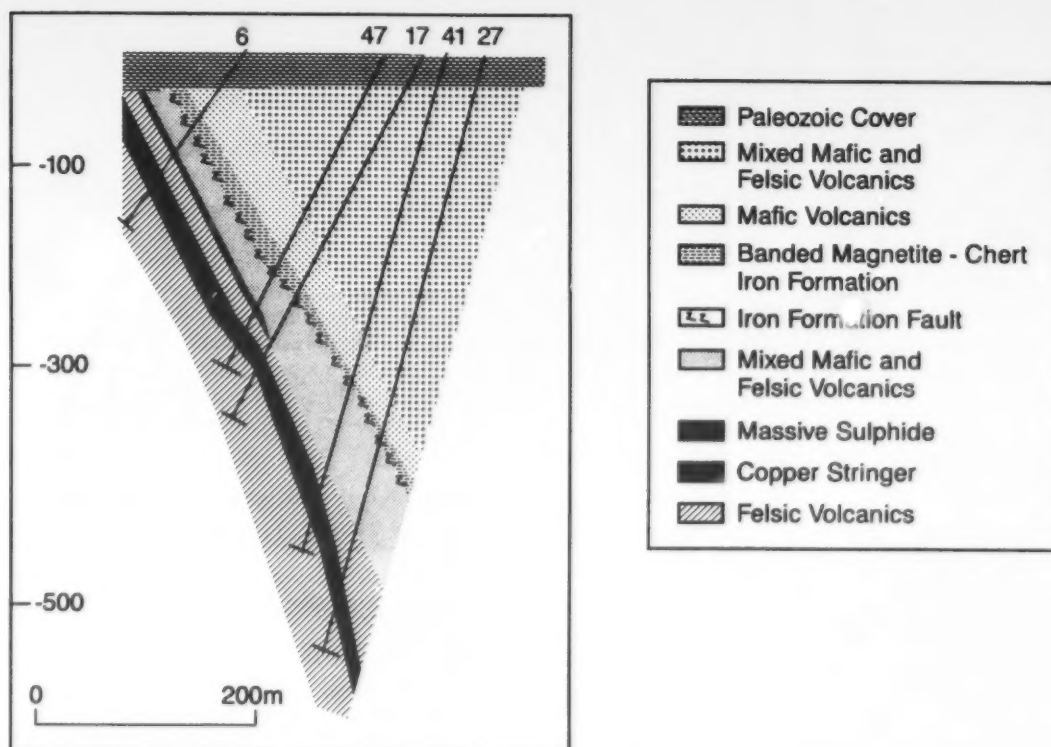


Figure 11 - Cross section 97+50 E looking 298° (McIlvenna Bay deposit).

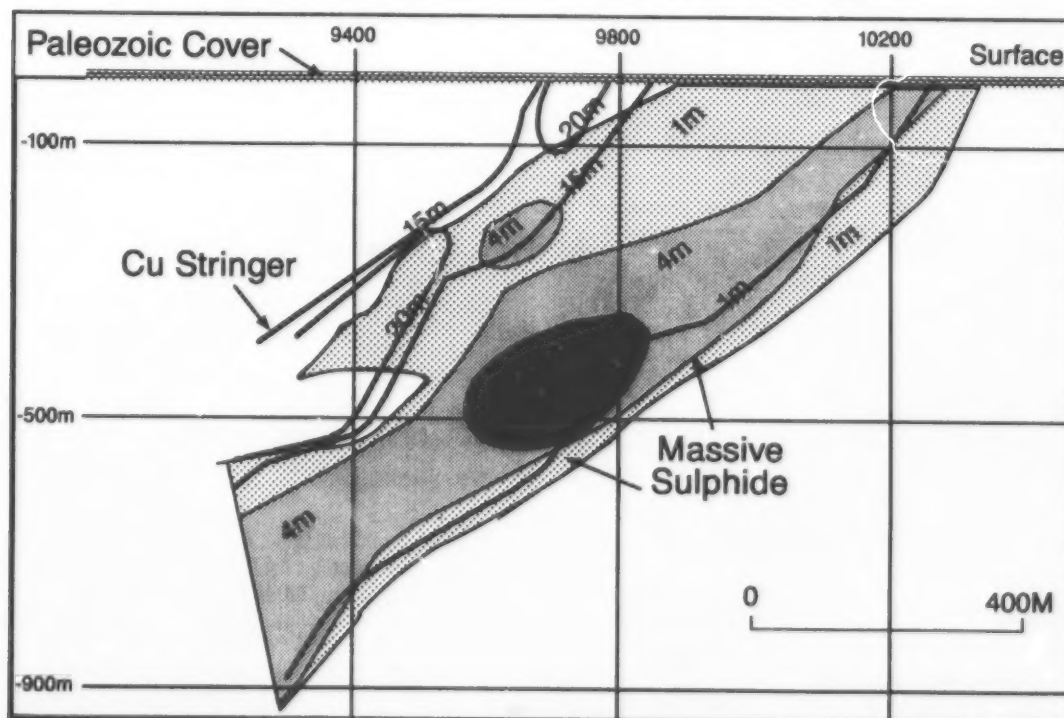


Figure 12 - Longitudinal section for Lens 2 (facing N.E.) of the McIlvenna Bay deposit showing the true thickness of massive sulphide and copper stringer.

deposit. Chloritized and sericitized blue quartz-pyritic rhyolite occurs towards the southeast. The chloritic alteration pipe related to Lens 2 exceeds 100 m thickness locally, and may contain up to 80 m of irregular stringer sulphide stockwork mineralization, which diminishes with distance from the massive sulphide lenses. Chalcopyrite is the most common sulphide phase. Carbonate and quartz are minor components commonly associated with silicification.

Relative aluminum enrichment is indicated by the occurrence of andalusite in the host dacite and pseudomorphs of andalusite in the massive sulphide lenses. Andalusite is more common in the northwest and most abundant in areas closest to the inferred hydrothermal vent(s) (Figure 13).

Strong sericitic alteration, occurring beneath the southeastern part of Lens 2, may be indicative of alteration zoning laterally away from the centre of the hydrothermal vent. Carbonate, a significant component of the alteration assemblage, is typically

restricted to the matrix of the massive sulphide portions of the deposit.

DISCUSSION AND CONCLUSION

The McIlvenna Bay deposit was discovered through implementation of classical base metal exploration strategy. The property was initially acquired on the basis of geological characteristics favourable for base metal exploration and then surveyed using airborne electromagnetic and magnetic methods. These surveys were followed up by prioritization of anomalies, completion of ground geophysical surveys, and subsequent diamond drilling. This work ultimately resulted in the discovery of the deposit in March, 1988.

The McIlvenna Bay deposit is typical of volcanogenic massive sulphide deposits, as described by Sangster (1972). It is stratabound and consists of lenticular bodies of massive and stringer sulphides which contain potentially commercial grades of zinc, copper, silver, gold and lead. The lenses lie along a mineralized horizon at or near the top of a felsic volcanic

cycle, as indicated by the thick accumulation of chert and banded iron formation.

The massive sulphide lenses have associated sericitic and chloritic hydrothermal alteration 'vents'. The copper stringer mineralization associated with Lens 2 is hosted within a prominent chloritic alteration vent.

As a model for deposit genesis, it is suggested that recurrent episodes of sea floor fumarolic activity, at the end of a major period of felsic volcanism, deposited sulphides as sediments in sea floor depressions on the flanks of a major felsic dome such as the one exposed at Hanson Lake. These sulphides were subsequently overlain by felsic and mafic tuffs, and volcanoclastic and chemical sediments. A schematic reconstruc-

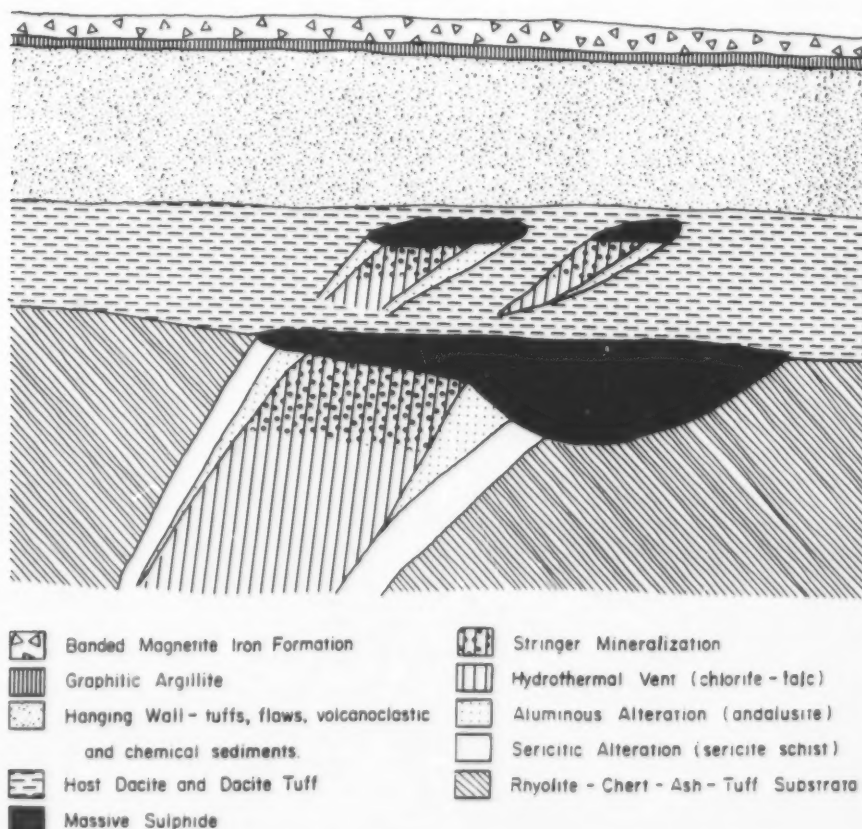


Figure 13 - Schematic reconstruction of the McIlvenna Bay deposit prior to deformation.

tion of this model is presented in Figure 13. Subsequent deformation sheared, transposed and elongated the lenses and associated stringer/alteration zones.

The exploration potential of the area is considered good. The deposit is open down plunge and to the northwest, and to date there has been no systematic testing for additional lenses in the plane of the mineralization.

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ACKNOWLEDGEMENTS

The authors wish to thank the management of Cameco - A Canadian Mining & Energy Corporation and Trimin Resources Incorporated for permission to present this paper. Acknowledgements and special thanks are extended to D. Bell, J. Halaburda, and J. Mattock, Cameco drill site geologists, for the professional job done during the diamond drill programs. We would like to thank D. Jiricka, R. Matthews, and K. Downes for their editorial comments on this manuscript. Further thanks are extended to B. Shaw for geophysical data processing, B. Senger for preparing the manuscript, and C. Durbin for drafting.

Uranium Exploration

AEROMAGNETIC VERTICAL GRADIOMETER AS AN EXPLORATION TOOL

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ABSTRACT

Aeromagnetic vertical gradiometer surveys have been completed over different areas in Saskatchewan, in various geological and structural environments. In all cases, the surveys have contributed to a better understanding of some aspect of the geology or structure. This arises because the data portrayed on the maps are a consistent, continuous, and objective portrayal of the distribution of the magnetic minerals in the underlying rocks. Therefore, the data has a direct correlation to some aspect of the geology. The magnetic method also penetrates overburden, water and swamps and is usually not affected by them. The interpretation of the magnetic maps therefore requires an understanding of the relationship between the magnetic components of the rocks and the geologic environments and structures.

In northern Saskatchewan vertical gradiometer surveys have been extremely useful in delineating structures within the Athabasca Group and in outlining the geology of the underlying basement and structures within the basement. Areas in Saskatchewan, adjacent to the Canadian Shield and covered by a blanket of Paleozoic rocks, are also areas which have already benefitted from the use of vertical gradiometer surveys. These surveys permit the extrapolation, at a reasonable cost, of Shield geology, into the basement areas which are buried. Surveys in the Shield itself also contribute to an understanding of the geology and structures, again because the data is detailed and continuous. Digital processing of the data can allow them to be displayed in a variety of derived maps, such as shaded relief, band-pass filtering, etc. Each map can contribute to a better understanding of the size, shape and inclination of various geological features and structures. The utility of vertical gradiometer data will be illustrated by several examples in Saskatchewan.

LARGE LOOP EM SURVEYS IN THE ATHABASCA BASIN

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ABSTRACT

Large loop EM surveys are the preferred method for delineating deep basement conductors. They fall into three categories: 1) fixed loop with a roving receiver; 2) continuous moving loop (or Slingram array); and 3) stepwise moving loop (or common receiver array). The first of these is favored for its economy and reliability. The second is used where the first fails to delineate accurately or in reconnaissance mode to identify favourable zones. The third is a hybrid of fixed and moving loop. In the Athabasca Basin, the moving loop methods are about four times as costly as fixed loop on a per kilometre basis. Labour costs are lower with stepwise than with continuous moving loop but this is offset somewhat by higher processing costs. Examples from four areas are presented.

Fixed loop surveys remain the preferred method in the Athabasca Basin. However they can suffer from ambiguities related to a conductive host, layered earth response, multiple conductors and conductive blocks. The conventional approach of surveying each line two (or more) times from opposing transmitter locations, can fail to deal with these problems adequately since it is difficult to know in advance what survey design is necessary for a given situation.

Moving loop involves moving the transmitter loop in tandem with the receiver coil. In this respect it is like the MaxMin system which is used in the shallower parts of the Athabasca Basin. The problems associated with continuous moving loop are: 1) careful design is essential to ensure an adequate signal to noise ratio; 2) susceptible to horizontal masking conductors; 3) anomaly wavelengths are not directly related to conductor depth as they are with fixed loop; 4) anomalies may be either positive or negative. These problems can be treated by combining moving loop with fixed loop and by modelling. A symmetric array employing leading and trailing receivers can beneficially be used to reduce the background noise in the data.

The stepwise moving loop array comprises a central transmitter loop with perhaps two dozen, two-component receiver measurements in profile through each loop. Loop moves are equal to the loop size and three fold loop coverage is commonly obtained at each station. Depth Image Processing can be performed in which the data are stacked and inverted into an imaged resistivity section which enhances stratigraphic features. More recently a second process has been developed in which correlation filters representing horizontal and vertical conductors at the expected depth are applied to the data; and with weighting according to loop location the results are combined into continuous profiles. This product compares favourably with both the fixed and continuous moving loop methods. A simple field procedure is described for enhancing conductor responses by applying a difference operator to receiver stations located symmetrically about each transmitter loop.

INTRODUCTION

Geophysical exploration in the Athabasca Basin in the decade of the eighties focused on the delineation of basement graphitic conductors which have a known association with uranium mineralization. Figure 1 shows a schematic model of an unconformity-related uranium deposit. There is usually a sheet-like, graphitic basement conductor in the immediate vicinity. The conductor typically occurs within metasedimentary gneisses which are commonly in contact with granitic gneisses. The metasediments have a higher conductivity than the granitic gneisses and may produce a broad conductive response which can confuse the EM survey results. There is normally a structural association in the form of a fault or shear with an associated chimney of hydrothermal alteration extending up toward the surface. A well developed conductive regolith typically occurs at the unconformity. The problem of delineating the basement conductors of the Athabasca Basin, particularly within this type of conductive environment, is the subject of this paper. Four case areas (Figure 2), selected on the basis of the variety of work and location, will be examined.

As uranium exploration has extended from the edges of the Athabasca Basin to the interior, the more

traditional electromagnetic techniques have been superseded by time domain electromagnetic surveys (TDEM) with large loops which currently delineate basement conductors to depths of 800 m. Although TDEM surveying in the Athabasca Basin began in the late seventies, it was the discovery of the Cigar Lake deposit with the aid of the Crone DEEPEM system in 1981 at a depth of 450 m which triggered a movement toward exploration in the basin's interior at significantly greater depths. Exploration with large loop time domain EM systems at that time took two forms: 1) **fixed loop** surveys in which the receiver roves along several lines off a fixed transmitter loop and; 2) **in-loop** surveys in which a transmitter loop and a central receiver sound along a profile to map the sub-Athabasca geology.

The three current large loop configurations, fixed loop, continuous moving loop and stepwise moving loop, are illustrated in Figure 3. Brief descriptions of their operation and characteristics are given below.

FIXED LOOP SURVEYS

Fixed loop surveys are about a quarter of the cost of the moving loop methods on a straight per kilometre basis and about half the cost assuming coverage from opposing pairs of fixed loops. The method is there-

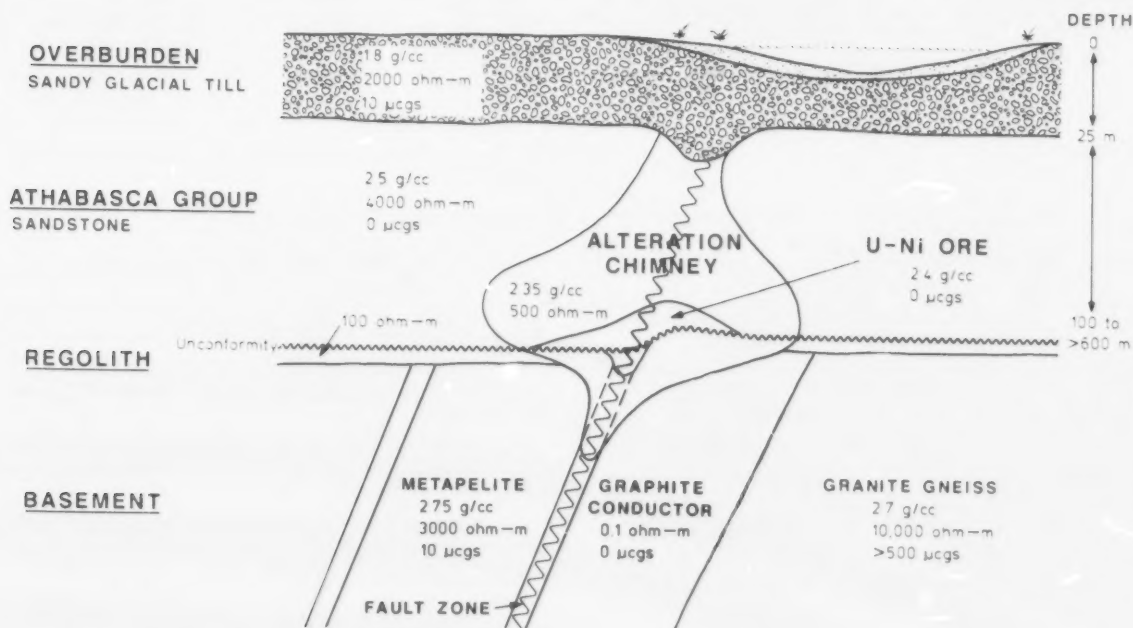


Figure 1 - Geophysical model of a typical unconformity uranium deposit in the Athabasca Basin (McMullen et al., 1989).

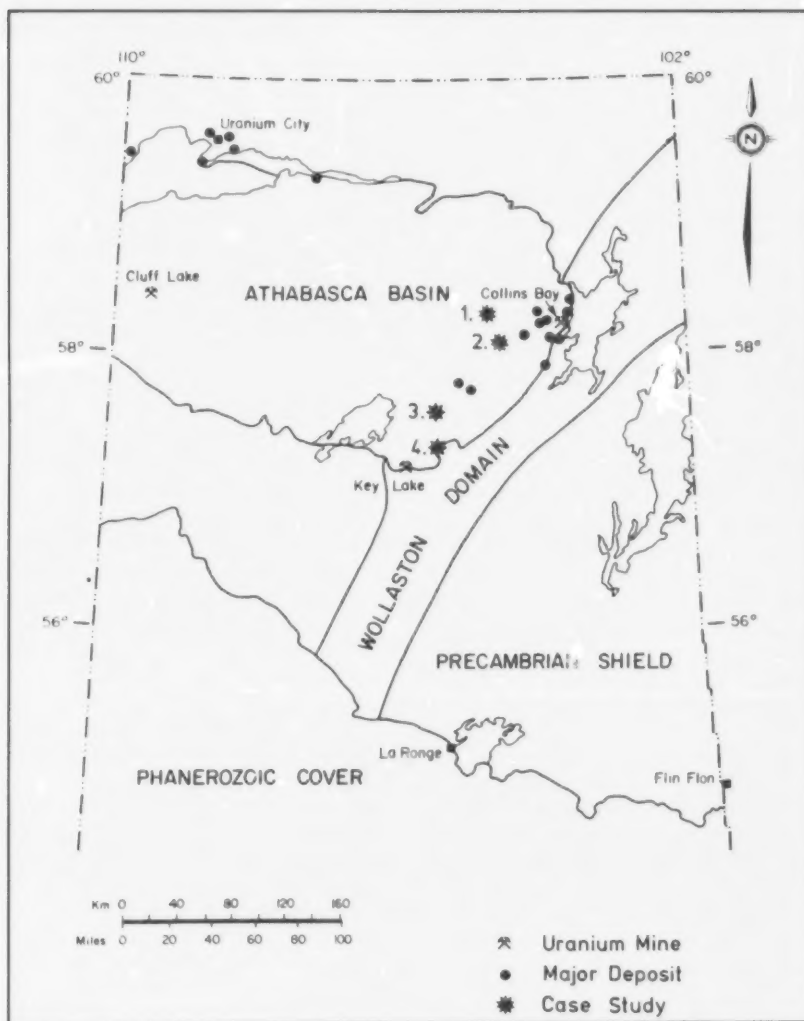


Figure 2 - Regional geology map of northern Saskatchewan showing location of the four survey areas.

fore likely to remain popular since it can delineate the deeper conductors of the Athabasca Basin without difficulty. Figure 4 shows 10 channel UTEM¹ responses generated with Multiloop² for a simple 15 siemens vertical sheet model at depths of 400, 600 and 800 m with and without a weak masking conductor of 5 siemens representing a well-developed regolith. The 400 by 400 m transmitter loop is 600 m to the right of the conductor. Typically both horizontal and vertical components are

recorded and interpreted. Responses are easily discernible vertical component cross-overs or horizontal component peaks with wavelengths directly relatable to the depth of the conductor. The addition of the weak horizontal masking conductor significantly complicates the results and adds asymmetry to the profiles which might mislead the interpreter. The implementation of a suitably placed opposing loop is necessary to deal with such complications. This would reveal a stacking of picks at mid to late times at the location of the vertical conductor. On the other hand if either loop were badly misplaced, an incorrect interpretation might still arise.

Other problems associated with the fixed loop methods are well known and have been described by various people. A good summary is given by MacNae (1985). Problems include the layered earth response and current channelling at geological boundaries (Spies, 1984) which can be loosely grouped together as geological noise. There are also limitations which are more directly related to the method itself. Notable amongst these is a limited ability to resolve closely spaced multiple con-

ductors or conductive blocks; loop position is commonly less than optimal without prior information.

CONTINUOUS MOVING LOOP

Recently, there has been a rising interest in continuous moving loop surveys which are carried out like a Maxmin³ survey (HLEM). The transmitter loop and receiver coil move in tandem at some fixed separation. The method, which has also been called

1) Lamontagne Geophysics Ltd., Toronto
2) Geopak Systems, Toronto
3) Apex Parametrics Ltd., Markham, Ontario

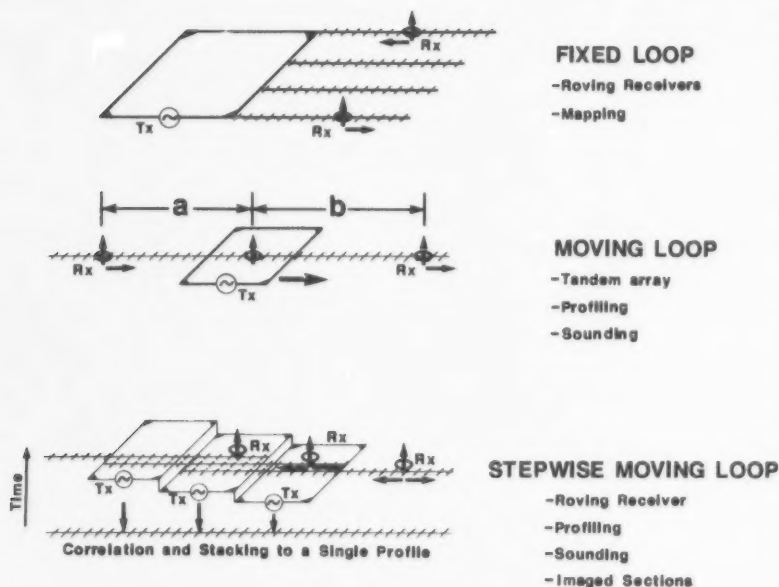


Figure 3 - Three configurations currently employed for large loop EM surveys in the Athabasca Basin.

'Slingram', 'HLEM', 'two-loop', 'tandem loop' or just 'moving loop', has a large transmitter loop which allows a greater primary field flux into deep conductors and larger transmitter - receiver separations than is the case with a small dipole transmitter allowing exploration at much greater depths. Normally the wire for the leading and trailing edge of each transmitter loop is laid out in advance while the sides are towed along adjacent cut lines with connections being made and broken at each corner. Since a rigid system geometry is maintained throughout, it is possible to make direct comparisons of response from one part of the profile to another. This constitutes an advantage over fixed loops, the response of which varies according to distance, depth and orientation of a conductor.

Maxmin surveys enjoy a significant cost advantage, being about a quarter of the cost or less of fixed loop, due to the lightness and mobility of the dipole transmitter. The use of a large transmitter loop, however, completely eliminates the cost advantage for moving loop surveys which are about twice as expensive as double fixed loop coverage due to the considerable labor required in moving large loops in a forest environment. Consequently the method is not likely to replace fixed loop surveys in the near future. It is a useful adjunct either as a reconnaissance tool prior to fixed loop coverage or as a followup survey to help sort out complex situations.

In the Athabasca Basin one or two receivers are used. These are typically located at 1.5 to 2 times the expected conductor depth from the centre of the transmitter loop to maximize the conductor response (Eaton and Hohman, 1985). Separations can be significantly smaller if resolution is the primary objective. Both leading and trailing receivers can be employed, in most cases at different separations, to maximize the extent of the coverage. It is also common to include a zero-separation in-loop receiver at the center of the transmitter loop as an aid to the interpretation of the results. Although its amplitude is not optimal Spies (1980 a-c) considers that the in-loop response has the advantage of being less complicated. Spies and Parker (1984) argue that the in-loop mode is less susceptible to current channeling effects which can lead to a

false interpretation.

The presence of both thick and thin sheet conductors can give rise to positive and negative anomalies which can lead to uncertain results with Maxmin. The same is true with moving loop data. So it is important to realize that a 'top' response (a coincident positive peak) can occur as easily as the dipping sheet response (a coincident negative peak) that people are accustomed to seeing with Maxmin. A top response is produced by an EM system coupling predominantly with the horizontal dimensions of a conductor. Some examples are a wide conductive block (Betz, 1976 and 1982), a conductive sphere (Ward, 1967) or a horizontal conductive sheet. An infinitesimally thin, dipping half-plane is the most common model for a dipping sheet response because of its simplicity. Whether a conductor gives rise to a top or dipping sheet response depends on its horizontal dimensions relative to the other dimensions of the survey, notably its depth and the transmitter - receiver separation (Ward, 1967). A top response is more likely to occur at separations which are small compared to the conductor depth. A good illustration of this is presented in a recent technical note published by Geonics Ltd. (1988).

Spies (1980 a-c) argues in favour of the in-loop configuration because the zero transmitter - receiver separation eliminates the sign ambiguity by guaranteeing a positive vertical component response to all

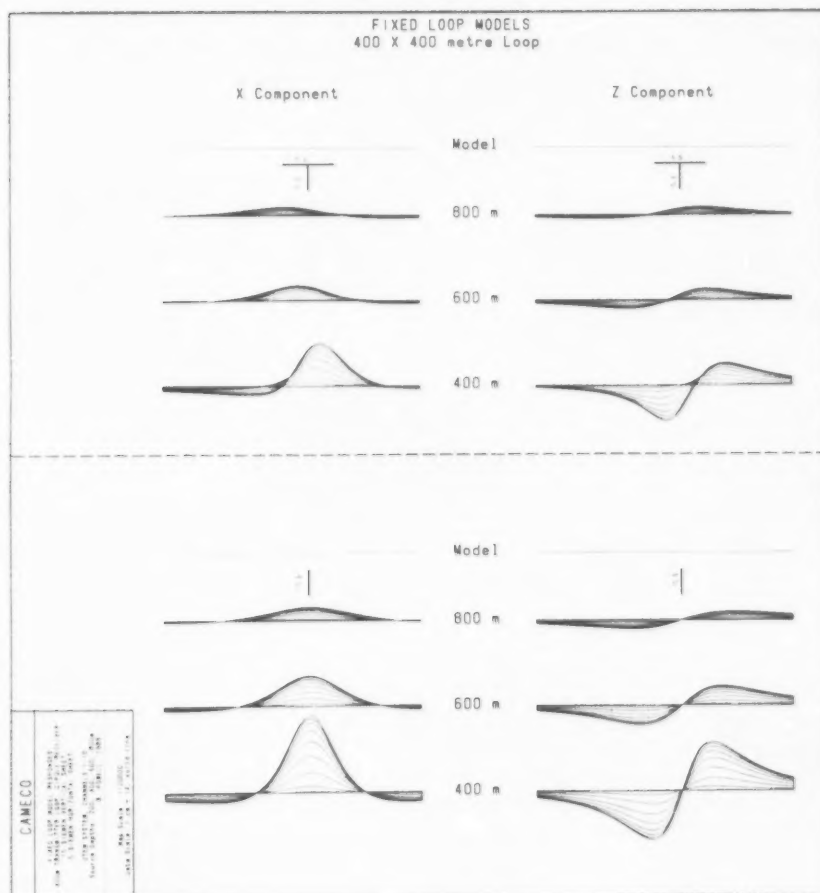


Figure 4 - UTEM3 fixed loop model responses of a 15 siemens vertical conductor at depths of 400, 600 and 800 m with and without a finite, 5 siemens horizontal masking conductor which is 600 m across. The transmitter loop is 400 m square and is located 600 m to the right of the vertical conductor. All responses are plotted at the same scale.

conductors. This is done, however, at the expense of the strength of the response relative to background noise which may be great in the vicinity of the conductor. In the Athabasca Basin the trend has been in the opposite direction toward larger transmitter-receiver separations and larger loops in order to increase the probability of a strong dipping sheet response. Transmitter loops as large as 600 m square and separations of 1200 m have been used.

Moving loop UTEM3 responses are shown in Figure 5 at the same scale as Figure 4 for the same 15 siemens vertical sheet conductor with a 400 x 400 metre transmitter loop and a 600 m transmitter-receiver separation. Typically both vertical and horizontal components are recorded. While a strong response is obtained at 400 m, it falls off rapidly below that depth. A slight asymmetry in the vertical

component data at small conductor depths is due to the inherent asymmetry of the array since the transmitter loop is necessarily much larger than the receiver coil. It is not usually discernible if the loop size is less than half the transmitter-receiver separation. The horizontal component data are inherently asymmetrical due to the pronounced asymmetry of that type of array, the conductor occurring between the peak and the inflection making for a more difficult interpretation than the vertical component. The addition of the 5 siemens horizontal masking conductor produces a strong tor response relative to the 15 siemens vertical sheet. It effectively masks the vertical sheet response which is discernible only in the last few channels at 400 m depth.

With moving loop the shape and width of an anomaly is largely determined by the transmitter-receiver separation rather than the depth of burial. Consequently it

is more difficult to separate a deep basement anomaly from surficial noise, such as fluctuations in overburden thickness, on the basis of anomaly wavelength. There is also objection to the labor intensive transport of the loop by one station interval at a time in order to maintain constant system characteristics without a corresponding beneficial change in coupling with the target conductor. For example, a 100 m station interval does not substantially change the coupling between the loop and a conductor at a depth of 600 m. A further objection relates to resolution of multiple conductors. With a transmitter-receiver separation which is twice the conductor depth, the resolution is about equal to the conductor depth, the same as fixed loop. Resolution can be significantly improved with a smaller separation but this is done at the expense of response.

STEPWISE MOVING LOOP

In the mid-eighties, the DIP (Depth Imaged Processing) sounding technique was developed which employs a hybrid of fixed and moving loop configurations. It was originally designed for generating imaged resistivity sections of the reflected layered earth response in a fashion analogous to seismic reflection sections (MacNae and Lamontagne, 1987). The transmitter loop remains fixed while a roving receiver reads through it. The transmitter loop is then stepped along the profile one full loop dimension before the reading process is repeated. Labor is minimized by employing the leading edge of each loop as the trailing edge of the next. Readings extend beyond the transmitter loop by one full loop dimension to produce three-fold loop coverage at each station. Consequently this technique can be regarded either as multiple fixed loop coverage or as moving loop

with a station interval equal to the loop size. This field procedure will be referred to generically as 'stepwise moving loop'. It is also referred to by Polzer *et al.* (1989) as a common receiver array.

As is the case with seismic reflection sections, the imaged resistivity section is effective for layered media but poor for steeply dipping features such as the basement conductors of the Athabasca Basin, though this information is present in the data. Consequently it was considered desirable to develop an alternative processing technique to extract this information from the DIP sounding data. Such a processing technique is described by Polzer (1988) who performed the correlation processing discussed in Area 2 below (Polzer *et al.*, 1989). In practice the process can be regarded as the successive application of a match filter, representing a desired conductor signature, to the data collected from each loop in turn. The results

of this process are combined into a single profile by stacking, with suitable weighting to generate the system response to the desired source. This is the approach taken by the writer in treating the data from Area 3. The practical effect of the weighting function is to: 1) take care of any change of sign of the response across each transmitter loop, and 2) lend greater weight to anomalies which are consistent with a well coupled conductor at a given depth and location for any given loop.

A number of simple models for approximating the desired source signature have been used. Analytical solutions for a vertical dipole source (top response), a horizontal dipole, a horizontal line of current, or a dipping sheet at the inductive limit have been used to approximate discrete conductors. The technique has been tested on models generated with multiloop and was found to compare favourably

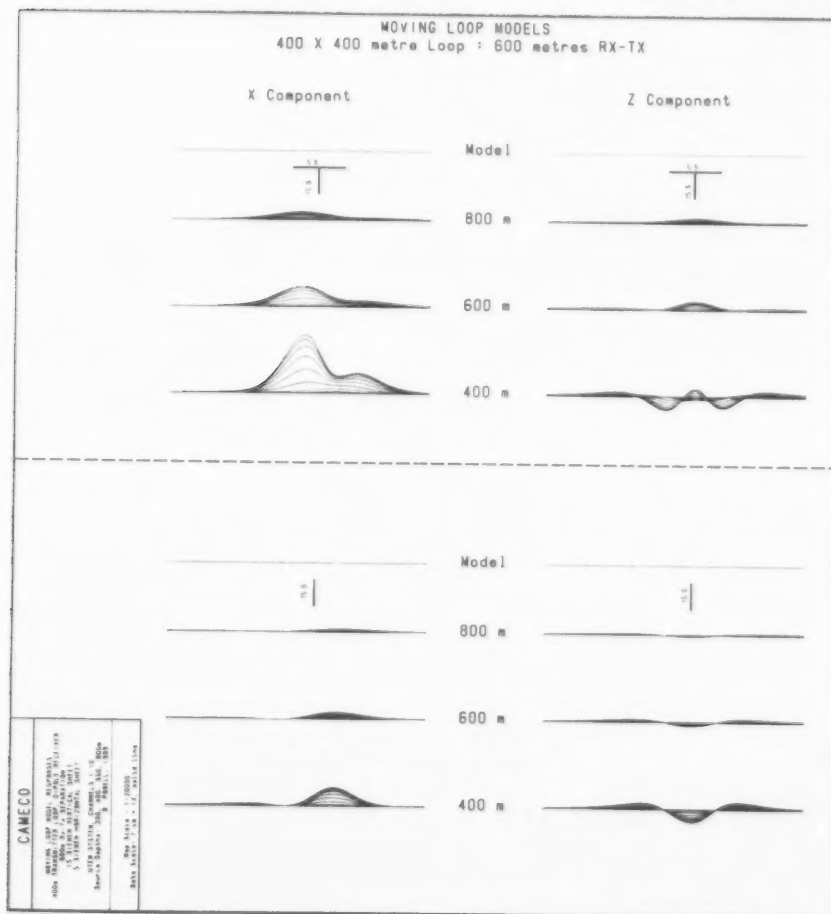


Figure 5 - UTEM3 moving loop model responses of a 15 siemens vertical conductor at depths of 400, 600 and 800 m with and without a finite, 5 siemens horizontal masking conductor which is 600 m across. The loop size is 400 m square and the transmitter - receiver separation is 600 m. The responses are all plotted at the same scale as Figure 4.

with the continuous moving loop method (Polzer, 1988).

A modelled layered earth response is sometimes fitted to the data and then subtracted before correlation processing to reduce the risk of a false indication of a discrete conductor. It is not clear at this point whether the benefits justify stripping because: 1) it is necessarily subjective, particularly when the data are less than ideal; 2) there is the risk that a real conductor response might be obliterated by excessive stripping; and 3) the layered earth response is suppressed to a large degree by the correlation processing itself. It is especially undesirable if one is searching for a top response which is similar in appearance to a layered earth response. While correlation with stripping was tried on both of the stepwise moving loop profiles described in this paper, none of those results are presented since there is generally a noticeable degradation of all responses, including conductors identified by other methods.

An objection expressed with regard to the use of a stepwise loop survey for delineation of basement conductors relates to the waiting time for correlation processing which typically has taken a few weeks after completion of the survey. This compares to a few hours of waiting for continuous moving loop surveys since these require little additional processing. The waiting time is diminishing with the advent of more powerful field computers and suitable field oriented software. Consequently it is likely that some on-site correlation processing will begin in 1990.

CASE HISTORIES:

Area 4 - Fixed Loop and Moving Loop

This case is a good example of how problems can be created by the top versus dipping sheet ambiguity associated with continuous moving loop. This area is situated near the extreme southeast corner of the Athabasca Basin due east of Key Lake. It is an area of shallow dipping metasediments and granitic gneisses striking east-northeast and overlain by about 200 to 250 m of Athabasca sandstone. Fixed loop surveys had indicated the presence of some poorly defined northwest-trending conductors. A northeast-oriented moving loop profile was performed with the EM37¹ time-domain system in order to clarify the nature of these conductors. Figure 6a shows the results of the moving loop survey and includes coverage from a fixed loop placed to the left of the profile. Both plots are inverted with respect to the conventional method

of presentation. The interpreter employed a thin, vertical conductor as his model at 2850. In the fixed loop data there is some evidence for such a feature in the channels shown. A fixed loop located on the right side of the profile produced no evidence of a conductor at this location.

Attempts to model the moving loop data produced the correct general shape but not the correct sign, as seen in the model plot at the bottom of Figure 6a. The model response amplitudes are also most similar at 2850 whereas in the field data they are most divergent at that location. It was subsequently discovered that the moving loop data were in fact recorded as positive numbers but were plotted as if they were negative. The anomaly in the moving loop data at 2850 is actually a positive top response as are two others at 2200 and 2500 occurring in early to middle time. Some modelling by the writer with Multiloop (Figure 6b) obtained the necessary positive response and shape with three 600 m wide horizontal conductors with strengths of 1, 3 and 12 siemens at locations 2200, 2500 and 2850 m and depths of 300, 450 and 550 m respectively. This configuration is more in keeping with the shallow dip of metasediments in the area and would account for the poor conductor definition encountered with the fixed loop data. No follow-up drilling has been carried out on this zone because the conductors do not appear to reach the unconformity.

Area 1 - Fixed Loop Versus Moving Loop

Area 1 is located north of the Cigar Lake deposit in the Cree Lake Mobile Zone. The basement geology comprises shallow basins of Archean metasediments unconformably overlying Archean rocks. The depth to basement is about 650 m. It has a complex system of northeasterly- to easterly- trending conductors which is complicated by the presence of what is interpreted to be a wide conductive host block. Consequently there are uncertainties about the precise locations of the conductors and their characteristics. A number of moving loop profiles were therefore conducted with the UTEM3 system to improve the understanding and accuracy in delineating the basement conductors.

The first moving loop profile, performed with a 400 m square loop and leading and trailing receivers at separations of 950 and 900 m respectively, was inconclusive. Figure 7 shows the vertical component data for the lead receiver at a separation of 950 m, plotted in Slingram mode. A weak dipping sheet response is evident at 700 S in the three earliest channels, 7 to

1) Geonics Ltd., Mississauga, Ontario

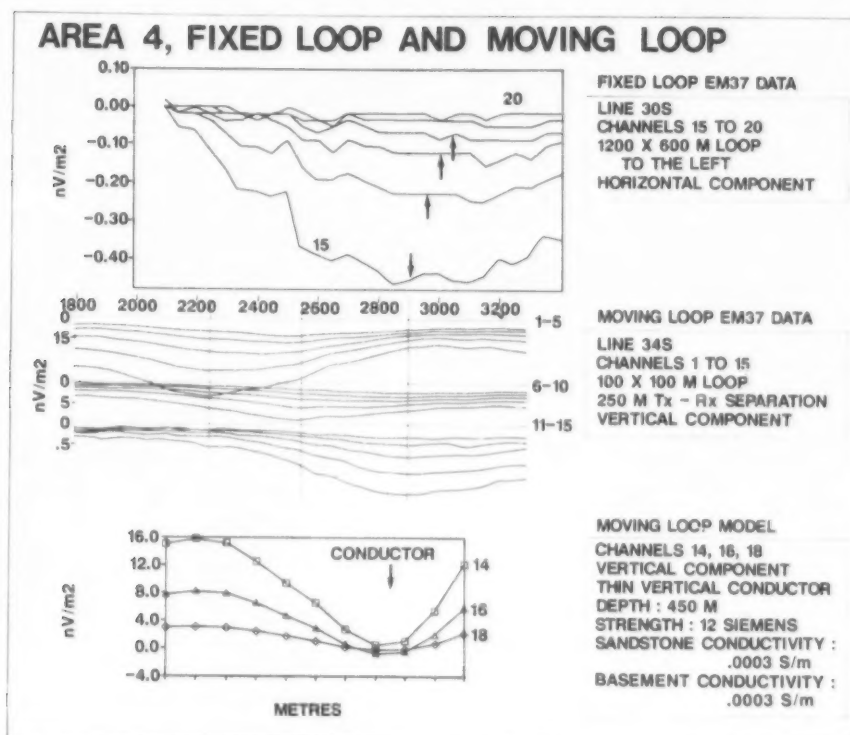


Figure 6a - Area 4, fixed and moving loop EM37 results and a vertical, thin sheet conductor model.

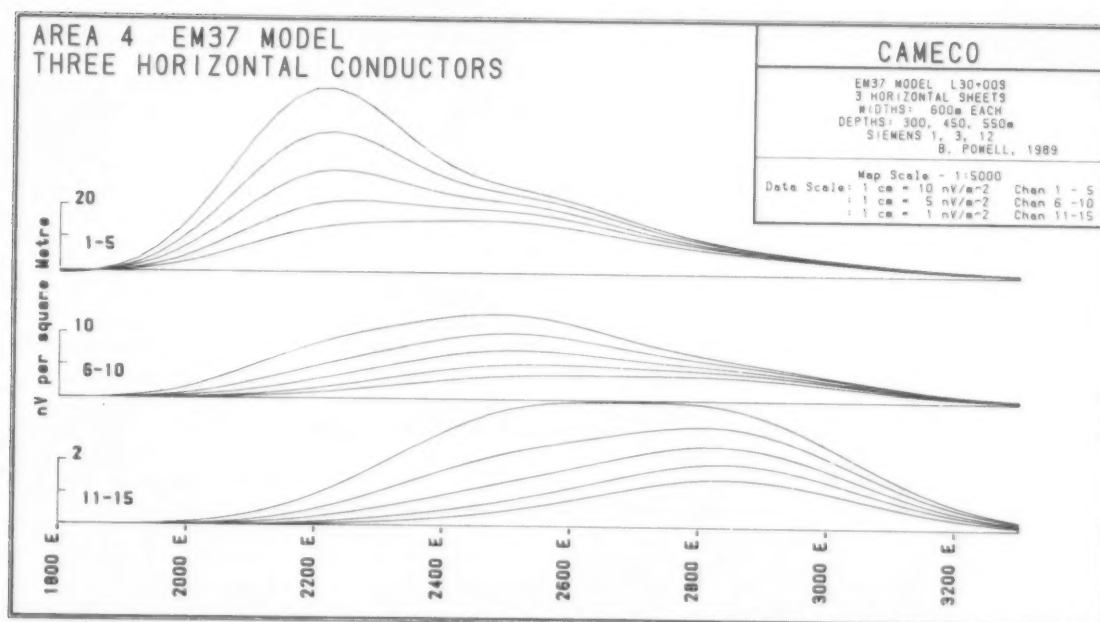
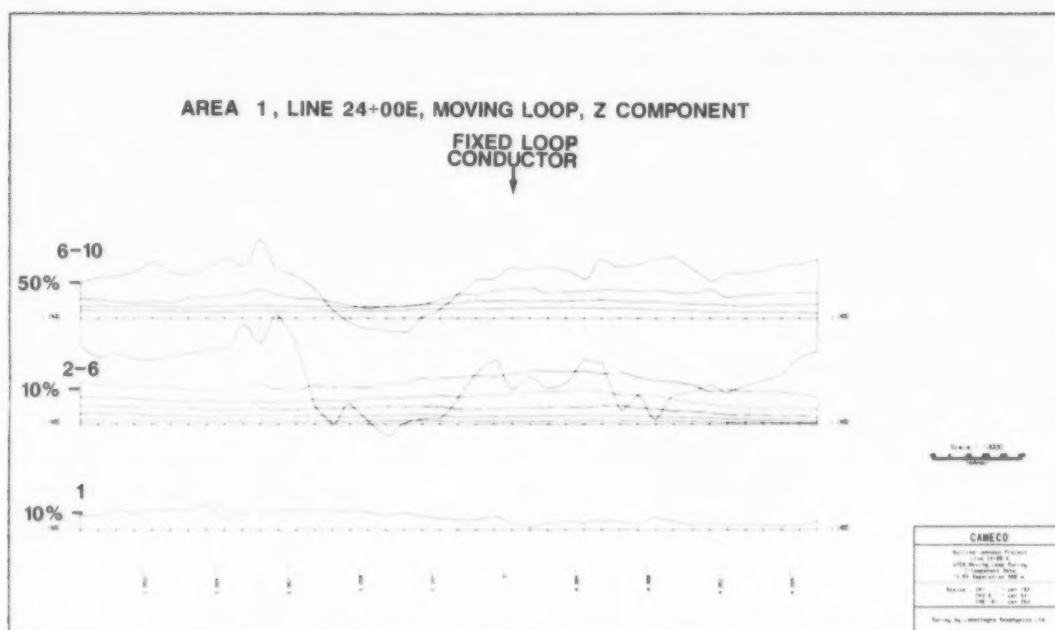


Figure 6b - Area 4, a model of moving loop EM37 results for three horizontal conductors 600 m wide with strengths of 1, 3 and 12 siemens at 2200, 2500 and 2850 m and depths of 300, 450 and 550 m respectively.



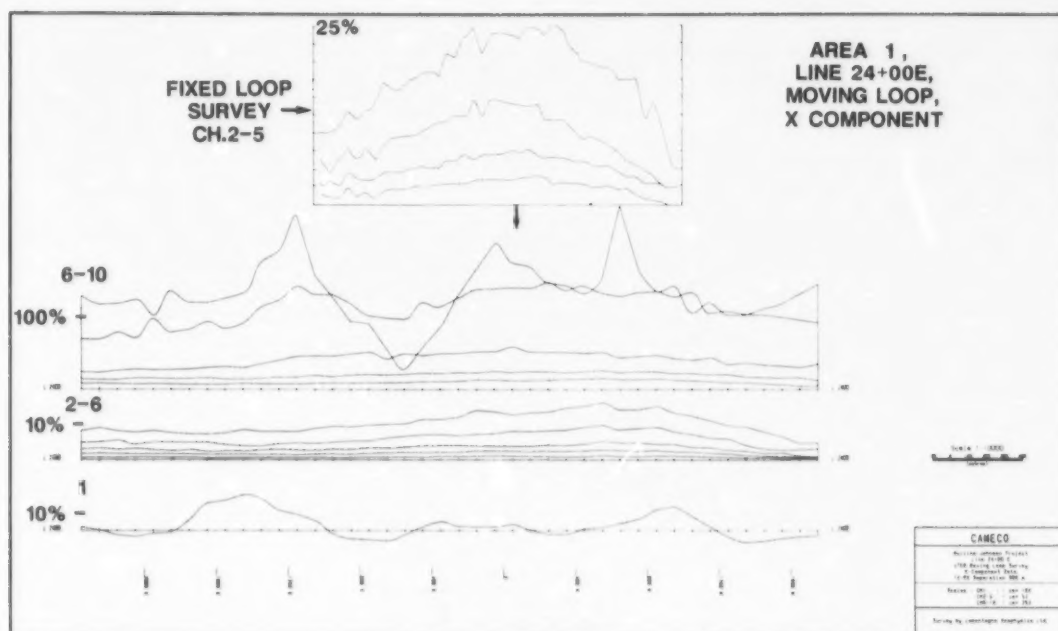
10. However a good fixed loop conductor just north of the baseline indicated by the arrow is not detected. There is instead a broad top response in the early to middle channels extending from perhaps 600S to 1000N which might represent a zone of more conductive basement or perhaps a conductive layer which is effectively masking the conductor in the vicinity of the baseline. Figure 8 shows the horizontal component data for the same profile, as well as channels 2 to 5 obtained from a fixed loop located to the north. Again it is evident that the baseline conductor, which is seen as a decisive positive peak by the fixed loop results, is unresponsive.

This example demonstrates that the masking effect of horizontal conductive features can be a problem with moving loop surveys in the Athabasca Basin. Consider a survey carried out with a symmetric array comprising a central transmitter and flanking receivers. The layered earth response can be expected to have a specific symmetry since it comprises reflected images of the transmitted field from horizontal conductive layers. The horizontal component is antisymmetric (opposite in sign) about the center of the loop whereas the vertical component is symmetric. Therefore, it is possible to cancel most of the layered earth response by adding (subtracting) the response of the horizontal (vertical) components at the two receivers for each location of the transmitter loop and then plotting the result conventionally at the center of the array. Figure 9 shows the effect this has on the moving loop model data of Figure 5. In

this case a perfectly symmetric super array has been employed where a equals b in Figure 2. A super array is defined here as an array employing more than one transmitter or receiver operated synchronously with a system response designed to enhance the signal from a specific type of target conductor. Spies (1980a) describes one such array obtained by employing a 'figure eight' transmitter loop.

The processing applied in Figure 9 will be described either as VX or VZ referring to the horizontal and vertical components respectively where V relates to a vertical sheet as the target conductor. In calculating the responses in Figure 9, the horizontal (vertical) component receiver readings were positive to the right of loop center and negative (set negative) to the left and were summed. The anomaly produced by the vertical sheet conductor alone is a cross-over response for both the horizontal and vertical components, though of opposite signs. This is understandable if one remembers that the primary field flux through a vertical sheet changes sign as the transmitter loop passes over it. The horizontal masking conductor confuses the horizontal component response to the vertical conductor less than the vertical component response which is opposite in sign.

The VX processed results of the Area 1 data are shown in Figure 10. It should be remembered that this particular survey was carried out with an almost symmetric array with leading and trailing receivers at 950 and 900 m from the transmitter loop. Only the



leading one is portrayed in Figure 8. Figure 10 was obtained by summing the leading and trailing readings and plotting at the loop center with no filtering or smoothing. A strong crossover with the correct sign, in the late channels 2 to 6, occurs just north of the baseline in good agreement with the fixed loop results. There is also a weak conductor indicated in channels 6 to 9 at 400S. This example demonstrates that the layered earth response can very effectively mask a conductor response. There is some merit in considering the use of a symmetric moving loop array with leading and trailing receivers to combat this problem, particularly if a small array is being contemplated in order to maximize resolution.

A diamond drill hole at 1+00N just west of line 24+00E intersected the unconformity at a depth of 648 m. The basement consisted of pegmatitic and in part weakly graphitic gneisses with abundant sulphides.

Subsequent UTEM moving loop profiles in this area were carried out with larger system geometries to increase the conductor response amplitude, although necessarily with some loss of resolution. Transmitter loops were 600 m square and leading and trailing receivers were employed at distances of 1000 and 1200 m. Figure 11 shows the successful vertical component results, for the leading receiver, plotted conventionally as if it were a Maxmin survey. Two weak conductors, A and B, are discernible in early to middle time. Conductor A dominates in early time, channels 7 to 8, while B tends to dominate in middle

times, channels 3 to 6. A strong third conductor C is visible in late time only, channels 1 and 2, between A and B. A hole sited on this conductor at station 1 + 00 SE intersected the sandstone-basement unconformity at a depth of 646 m. The basement consisted of chloritic schists and graphitic metapelites with locally abundant sulphides.

Evidence of all three conductors is present in the fixed loop data included in Figure 11. Conductor A is seen as a dominant central peak while B is seen only as a weak shoulder on the A anomaly because it is strongly masked by A from the transmitter loop which was to the left of A. Conductor C appears in the fixed loop data as a strong late time response in channel 1 only.

Area 2 - Cigar Lake - Continuous Versus Stepwise Moving Loop

This example provides an excellent opportunity to compare results of continuous and stepwise moving loop carried out on the same line. The results are shown in Figure 12. Fixed loop surveys had been carried out in the vicinity of the baseline several years before. The moving loop profile extends several kilometres beyond the original fixed loop coverage to appraise the potential for additional conductors. The basement in the area comprises primarily metapelites with overlying calc-silicate gneisses and local anatectic pegmatoids. The graphitic basement conductors are oriented east-west within a regional northeasterly trend. The depth to basement is about 450 to 500 m.

Conductors B and D had been previously delineated by fixed loop surveys while conductors A and C are outside previous coverage.

Leading and trailing receivers were employed for the moving loop work with separations of 1200 and 800 m respectively. The transmitter loop was 600 m square. Ten channel UTEM3 readings were taken at 100 m intervals. All four conductors were detected by the 1200 m array while only A, B and C are seen with the 800 m array. Both arrays are so large (1.8 and 2.7 times the conductor depth) that resolution is no better than fixed loop. Large arrays have been employed to maximize response at the expense of resolution.

A 500 x 400 m loop was employed for the stepwise moving loop survey shown in the lower half of Figure 12. All four conductors, A to D, are defined by correlation processing with a vertical conductor signa-

ture approximated by a horizontal dipole source at a depth of 700 m. The match with the moving loop results is very good with the largest difference being about 100 m for conductor B. Conductor C has the weakest response in both surveys appearing merely as a shoulder in the correlation processed results.

The plot at the bottom of Figure 12 was obtained by applying correlation processing with a horizontal conductor signature approximated by a vertical dipole source. There is an elevated top response indicating a conductive layer or block of conductive basement between conductors A and D. It is particularly strong between B and D.

Area 3 - A Closer Look At Stepwise Moving Loop

A stepwise moving loop profile was carried out in this area in 1986 employing a 20 channel UTEM system with the objective of producing an imaged resistivity section. The transmitter loop employed was 400 m square and the station interval was 50 m, the maximum transmitter - receiver separation being 650 m. Only the vertical component was measured and recorded. It was expected that the results would aid the geological interpretation of the area and provide a means of assessing the value of the technique in the Athabasca Basin. This section was subsequently published in Proceedings of Exploration 87 (McMullen *et al.*, 1989). The area is about 40 km north of the Key Lake mine site on the western edge of the Wollaston Domain. The basement comprises semi-pelitic gneisses, which are locally graphitic, and numerous northeasterly trending granitic gneiss domes which are very weakly to very strongly magnetic. Within the metasediments there are a large number of northeasterly-trending graphitic, moderate to very strong

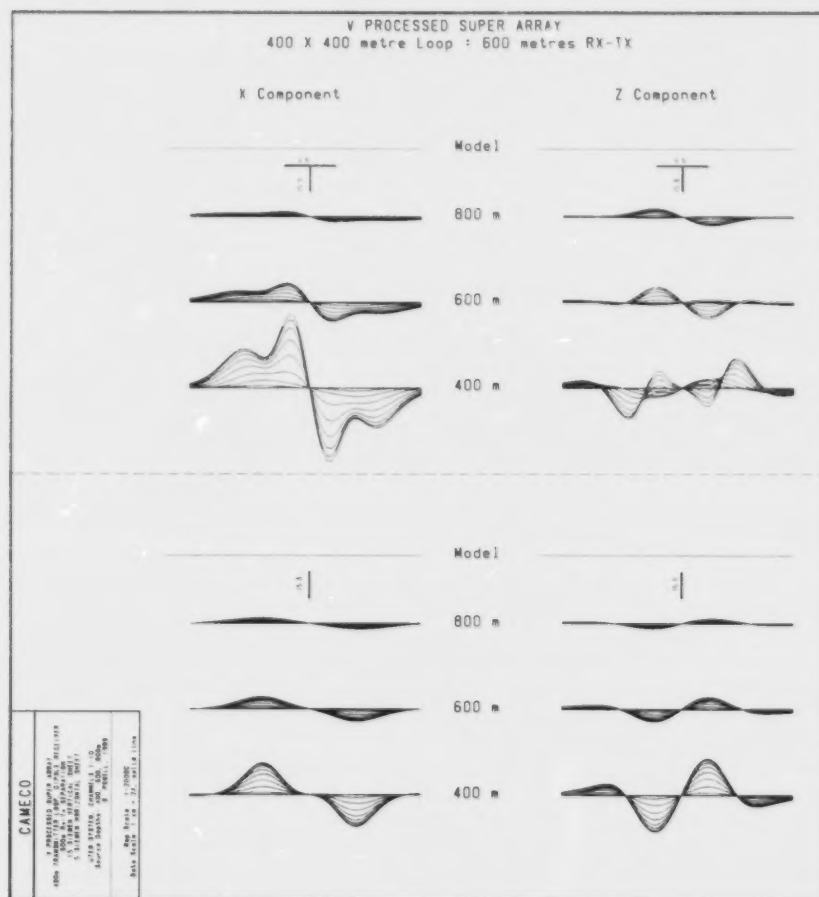


Figure 9 - UTEM3 VX and VZ processed super array responses of the moving loop model results of Figure 5. The responses are plotted at half the scale since they are about twice as large overall.

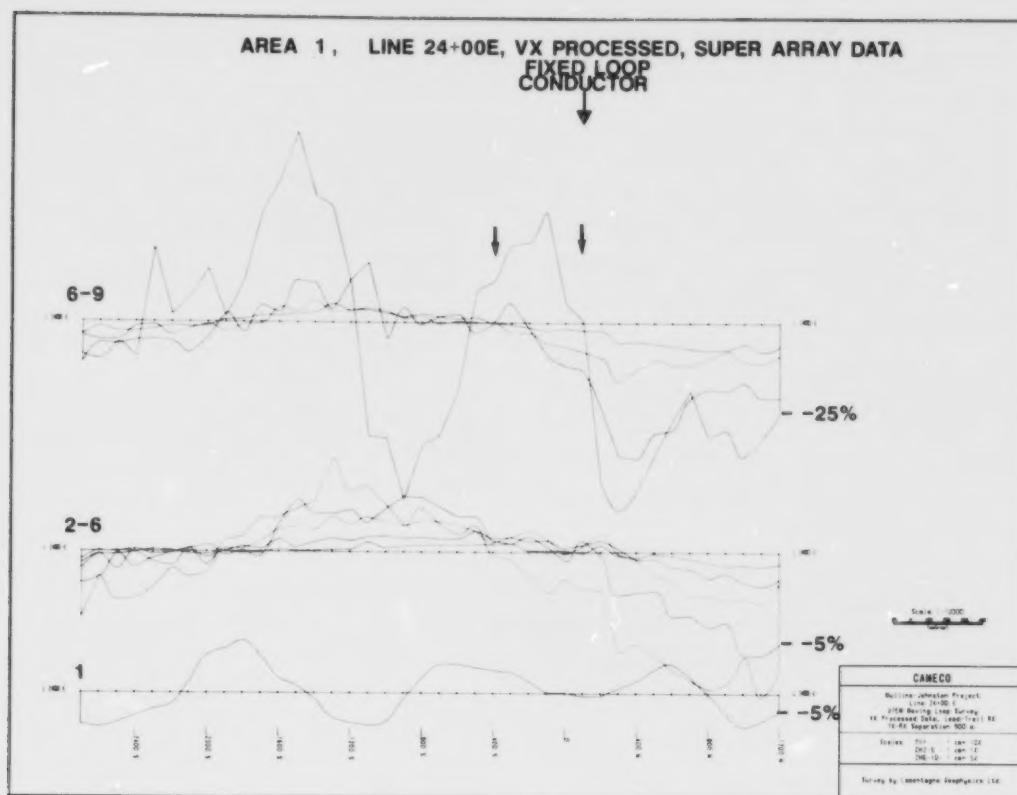


Figure 10 - Area 1, VX processed moving loop data, horizontal component, line 24+00E.

conductors. Conductivity thickness values range from a few siemens to more than 100 siemens. The basement depth varies from about 550 m at the east end of the profile to 640 m or more at the west end.

In 1989, the writer pursued the possibility of extracting whatever conductor information might be contained in the data. Correlation processing of model data generated with Multiloop using the Area 3 array indicated that vertical sheet conductors, at a depth of 600 m and as little as 300 to 400 m apart, should be resolvable. The results of correlation processing applied to the stepwise moving loop data using a top response signature are shown in Figure 13. The signature was approximated by a vertical dipole source at a depth of 600 m. A three point smoothing operator has been applied to improve the appearance of some of the earliest channels. The locations of the known fixed loop conductors labelled A1 to A6a are indicated along the upper portion of the plot. A zone of strong top responses occurs between the A3 and A1 conductors. Top responses coincide with the A1, A3, A5 and A6a conductors indicating that these have significant widths. Conductors A1, A3 and A5 were previously thought to have significant widths based either on fixed loop responses or drilling results.

Very little is known about conductor A6a which is largely masked from fixed loop detection by adjacent conductors. Conductor A3, which has an estimated strength of about 40 siemens, has a much larger early time amplitude than A1 which is known from fixed loop measurements to have conductivity - thickness values in excess of 100 siemens. This suggests that conductor A3 either has a zone of conductive alteration above it or is better coupled in some other fashion. Both conductors have been easy to intersect and are at nearly identical depths of about 640 m in this area. Conductor A3 is known to have significant sandstone alteration associated with it whereas the conductor A1 does not.

The results of correlation processing applied to the same data using a vertical sheet conductor response signature are shown in Figure 14. The signature was approximated by an infinitely long, current carrying, horizontal wire at a depth of 700 m. The depth chosen for presentation was arbitrary since results are not significantly different at a source depth of 600 m. A low pass filter with a 600 m cutoff was applied to improve the appearance of the results which were distorted at some loop boundaries, notably the anomalies at 4200 and 5000. This is due to the very

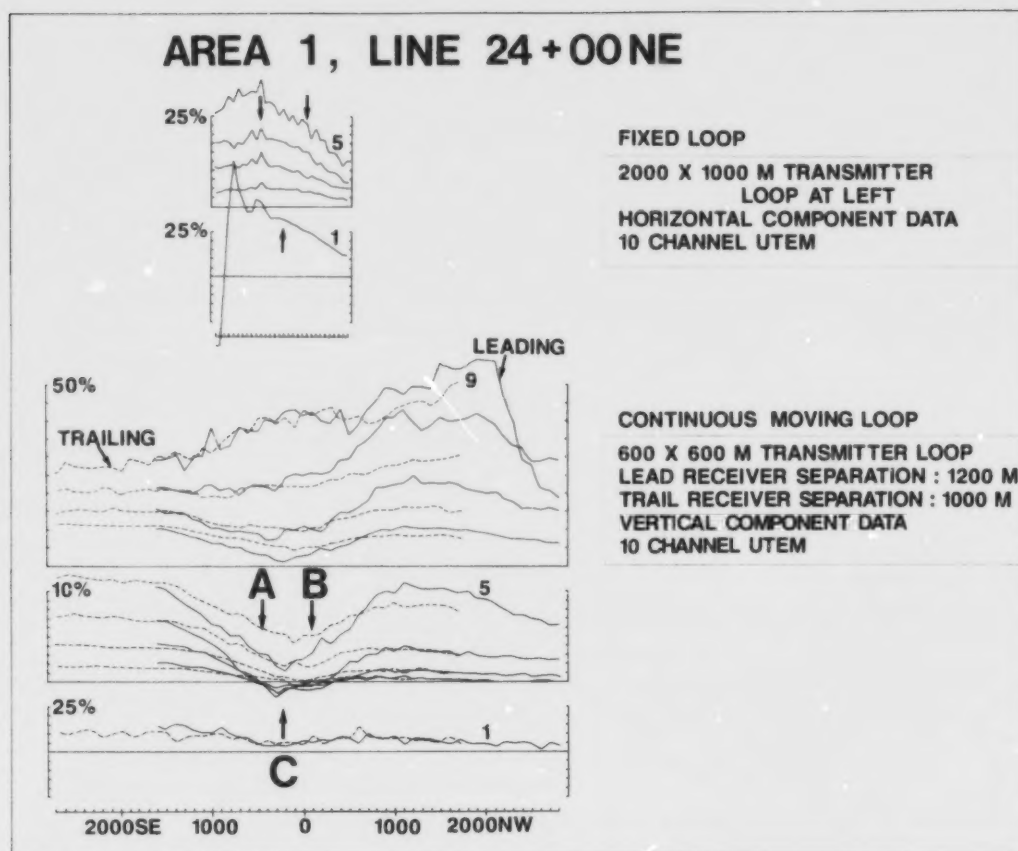


Figure 11 - Area 1, moving loop results, vertical component, on line 24+00 NE.

short size of the receiver array, about 1300 m in total length, compared to the wavelength of the source signature. The distortion could be reduced by employing an array size more appropriate to the expected anomaly wavelength. This could be achieved by obtaining four fold coverage instead of three fold for example.

A strong vertical sheet correlation, which persists to very late time, occurs about 125 m west of where the A6 conductor was located by fixed loops. This particular conductor, which was assessed at about 40 siemens, has proven to be particularly difficult to intersect, having been missed by two drill holes sited on fixed loop picks. The correlation processing suggests that this is because: 1) it is a thin vertical sheet and 2) it is further west than was previously thought. The fixed loop results are known to be distorted by the nearby A2 and A6a conductors. The basement geology intersected in the two drill holes also suggests that the conductor is to the west.

A vertical sheet response also occurs at conductor A2 and another occurs at a poor fixed loop conduc-

tor which was left unnamed, indicated in Figure 14 by a question mark at 5000 between the A1 and A3 conductors. A fourth vertical sheet response occurs at 4200 between the A5 and A3 conductors where there is no known fixed loop conductor but where a suspicion of a possible conductor was also previously noted.

Spreadsheet Applications

It is helpful to examine slices of the stepwise moving loop data of Area 3 with the aid of a spreadsheet program. This can be quickly done before or after correlation processing to get an idea of what the results should look like. Figure 15 shows a conventional Slingram (Maxmin) plot of receiver amplitudes at a transmitter receiver separation of 650 m. A broad top response is seen between the A5 and A1 conductors. Individual conductors cannot be discerned although it narrows considerably in late time channels 2 to 4 where it is centered on the strong A1 and A1' conductors. Further east there is a weak vertical sheet response in channels 2 to 8 centered on the A2 conductor. Nothing else is discernible primarily be-

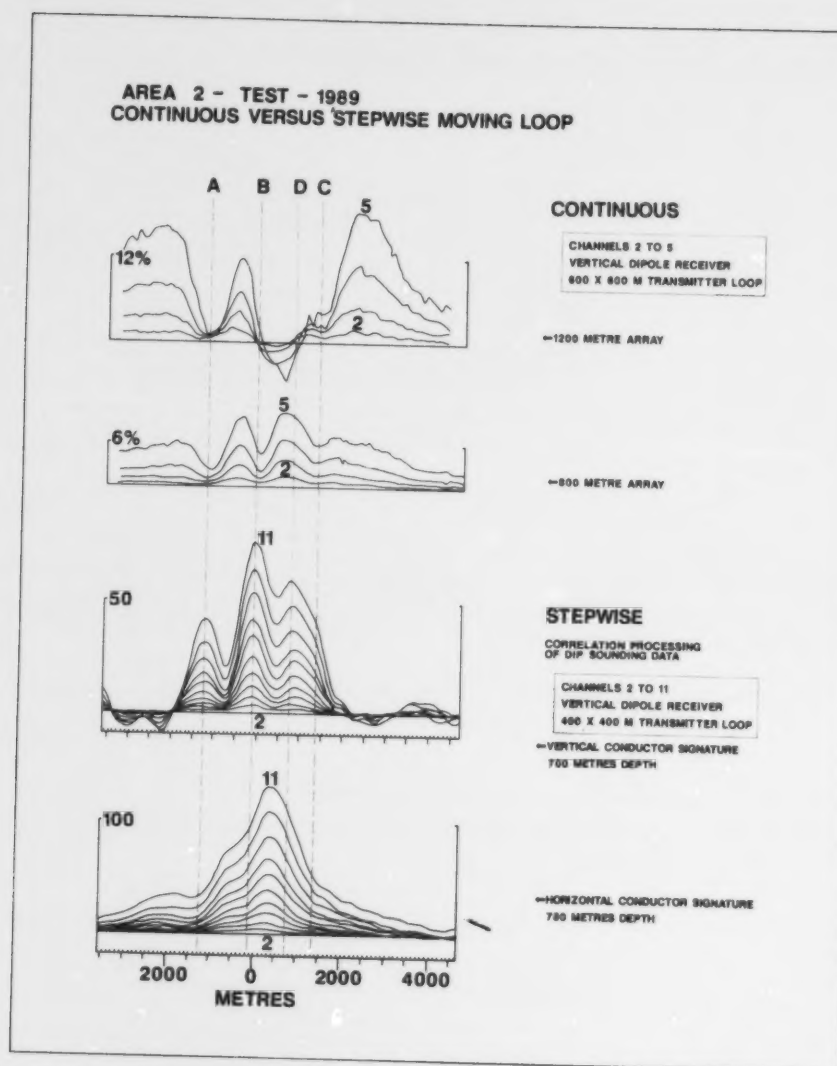


Figure 12 - Area 2, a comparison of continuous and stepwise moving loop UTEM3 results. They are from top to bottom: 1) continuous with a transmitter - receiver separation of 1200 m; 2) continuous with a transmitter - receiver separation of 800 m; 3) stepwise with correlation processing using a vertical conductor image (horizontal dipole); 4) stepwise with correlation processing using a horizontal conductor image (vertical dipole).

cause the anomaly responses are too small to be seen above the background noise.

An early time (channel 15) slice of the 20 channel UTEM data is shown in Figure 16, again plotted in Slingram mode with a wide variety of different transmitter - receiver separations. However in this case, both the leading and trailing receiver data have been plotted to make use of the entire data set. It is likely that some distortion of individual responses is occurring due to the significant size of the transmitter loop in which case it is desirable to be able to examine both leading and trailing responses. The results at

400 m separation are the average obtained with leading and trailing receivers since they plot at the same points, at the edges of the loops. At short separations of 100 to 300 m a strong positive top response is centered on the A3 conductor and there are what appear to be vertical sheet responses just west of the A2 and A6 conductors. All are likely related to shallow conductive features such as fault zones in the sandstone in the vicinity of these conductors and may be interesting for that reason.

It is possible to reduce the background noise in moving loop data by taking advantage of the symmetry inherent in the layered earth response as was shown with the Area 1 data. Stepwise moving loop data is particularly well suited to this calculation since measurements are made right through the loop. Figure 17 shows the VZ processed results at a transmitter - receiver separation of 650 m. The top and vertical sheet model responses for a conductor at a depth of 600 m are included for reference. This process clearly puts the A1-A1'

conductors into a position of dominance with strong late time top responses consistent with the fixed loop results. A good top response also occurs in the vicinity of the A3 conductor in middle to late time. A possible vertical sheet response is seen in the vicinity of the A2. Some anomalies are clearly ambiguous due to interference from adjacent anomalies.

When the same VZ processing is done with a smaller transmitter - receiver separation of 400 m, the results of which are shown in Figure 18, three significant things are noted: 1) Conductor A3 produces the

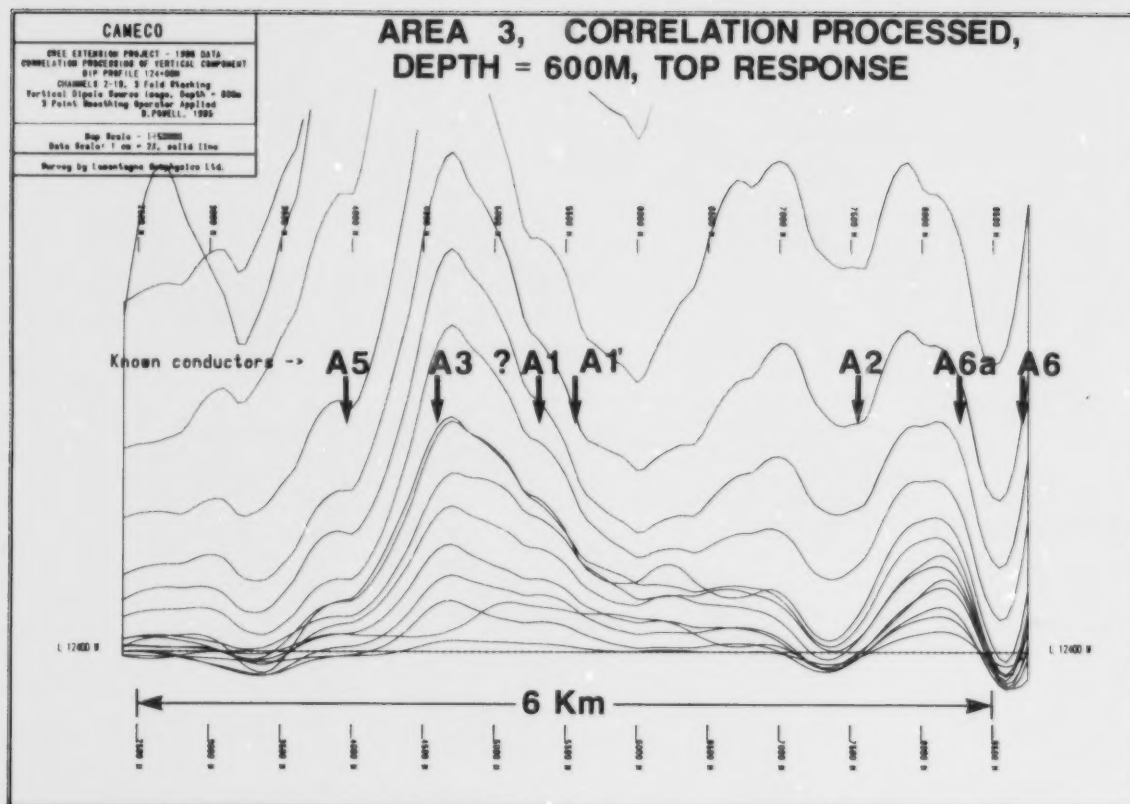


Figure 13 - Area 3, correlation processing of UTEM stepwise moving loop data, vertical component, with a top response approximated by a vertical dipole at a depth of 600 m.

dominant top response while A1 is discernible in very late time only; 2) conductor A2 has changed from a sheet response to a top response; 3) conductor A6 appears to remain a sheet response. It is concluded that conductor A3 is much better coupled at small separations than are the A1 and A1' conductors. It is also concluded that conductor A2 is not as broad as the A1, A3 and A5 conductors but is broader than conductor A6 which seems to produce a vertical sheet response even at quite small transmitter - receiver separations.

Image Processing

Finally, there is an alternative presentation of correlation processing which provides a picture of conductive features. The Area 3 profile is presented in Figure 19 as an imaged section produced by applying a top response source at depths from 100 to 800 m. The two images represent the late and middle time channels 5 and 10 respectively. As a wide range of depths are examined, this approach has the potential to provide information about structure and alteration as well as the location of the basement conductors. In the case of Figure 19, it is evident that much of

this information is occurring above the sandstone - basement unconformity indicated by U/C. This is not surprising since the relatively small array size employed for the Area 3 profile is less than optimal for the basement conductors but is favourable for shallower conductive features within the sandstone.

Since Figure 19 is a top response image, it should convey information about conductive features with significant horizontal dimensions, such as pervasive alteration, as opposed to a discrete fault. Bearing this in mind, there are two such zones which persist to late time and evidently extend to surface at conductors A3 and A6a. At A3 the alteration appears to be controlled by an easterly-dipping structural feature which intersects the unconformity about 75 m east of A3. A drillhole sited at A3 on this profile encountered moderate to strong bleaching, limonitic staining and clay filled cavities in the sandstone to a depth of 250 m. The basement in this hole is graphitic and exhibits moderate to strong hydrothermal alteration and elevated radioactivity. Conductor A6a has not been investigated.

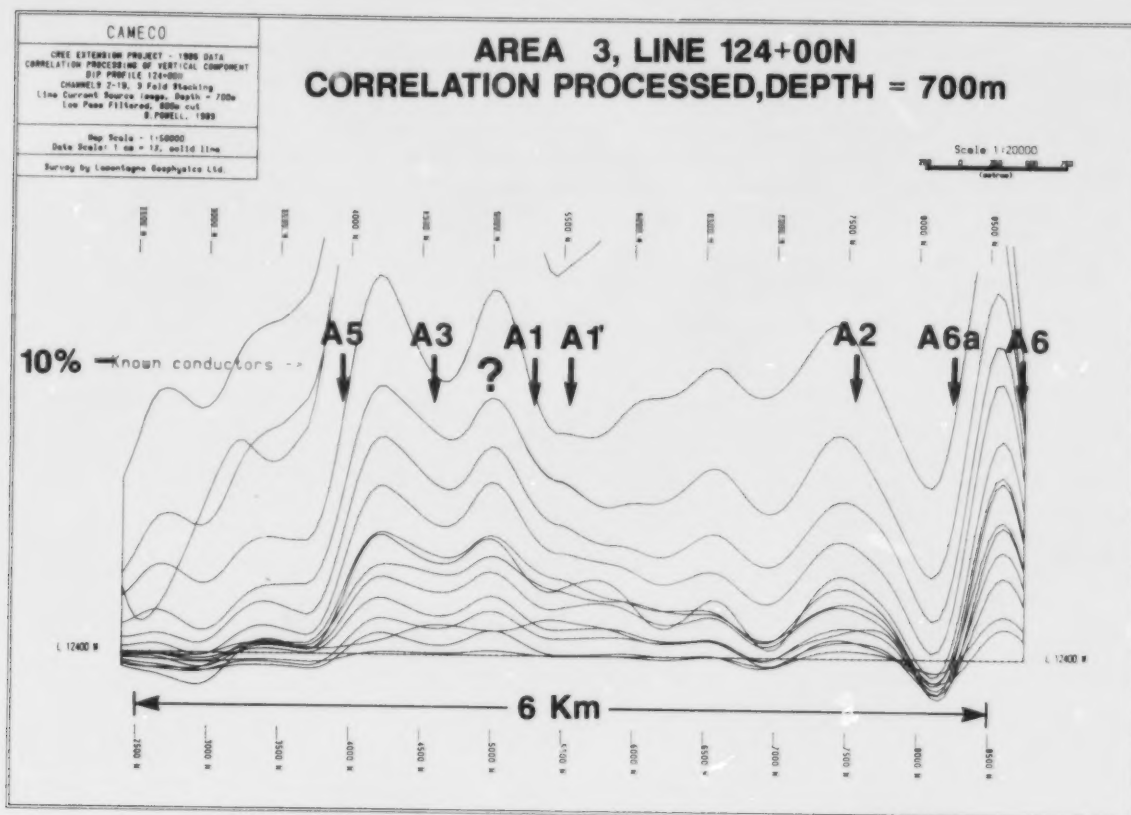


Figure 14 - Area 3, correlation processing of UTEM stepwise moving loop data, vertical component, with a sheet response approximated by a long wire at a depth of 700 m.

CONCLUSION

Comparing the large loop methods employed in the Athabasca Basin, fixed loop is the least expensive and constitutes a reliable and effective means of delineating deep conductors in most situations provided the survey design is adequate. The results can be confused by complex situations such as a strong layered earth response, multiple conductors, conductive host blocks, or masking conductors. Consequently the need arises for an alternative method which will provide a second perspective from which to deduce the conductor geometry.

Continuous moving loop has the advantage of a constant system geometry which avoids the 'footprint' problem of a fixed transmitter loop. It has enjoyed popularity in the sparsely vegetated areas of Australia where it is comparable in cost to fixed loop surveys. However in forested areas, like the Athabasca Basin, the per kilometre cost is about twice that of double fixed loop coverage. Consequently it is important to apply the method with discrimination and to understand the shortcomings of the method such as: 1) a sensitivity of response to conductor depth; 2) masking by conductive layers and other geological

noise; and 3) a sign ambiguity related to top response versus dipping sheet response. The trend toward ever larger arrays to obtain a strong dipping sheet response occurs at the expense of resolution. In some moving loop surveys the resolution is no better than fixed loop coverage. A symmetric array consisting of a central transmitter with leading and trailing receivers allows smaller separations by affording a means of cancelling the layered earth response.

The stepwise moving loop approach has good potential for mapping conductors at great depth because: 1) it requires less labour per kilometre than continuous moving loop; 2) it possesses the advantages of both fixed and moving loop surveys; 3) it deals effectively with the pitfalls of the continuous moving loop method, notably sensitivity to conductor depth, masking conductors and the sign ambiguity associated with anomaly responses; 4) it produces a better resolution of conductors than fixed loop. At the moment, the greatest impediment to the method is its greater processing requirements. The correlation processing performed by the writer for area 3 was completed on a Compaq III personal computer in a reasonably short period of time, about an hour

and a half per source signature. Furthermore, the larger database obtained with stepwise moving loop provides the interpreter with a greater variety of perspectives from which to view the data, with the aid of a spreadsheet program, than is available with either fixed or continuous moving loop.

It seems likely that the evolution of EM techniques in the Athabasca Basin will include the use of super arrays designed to focus on particular types of target conductors. These may be as simple as the VX and VZ processing described here or as sophisticated as the correlation processing method described by Polzer *et al.* (1989) for stepwise moving loop data.

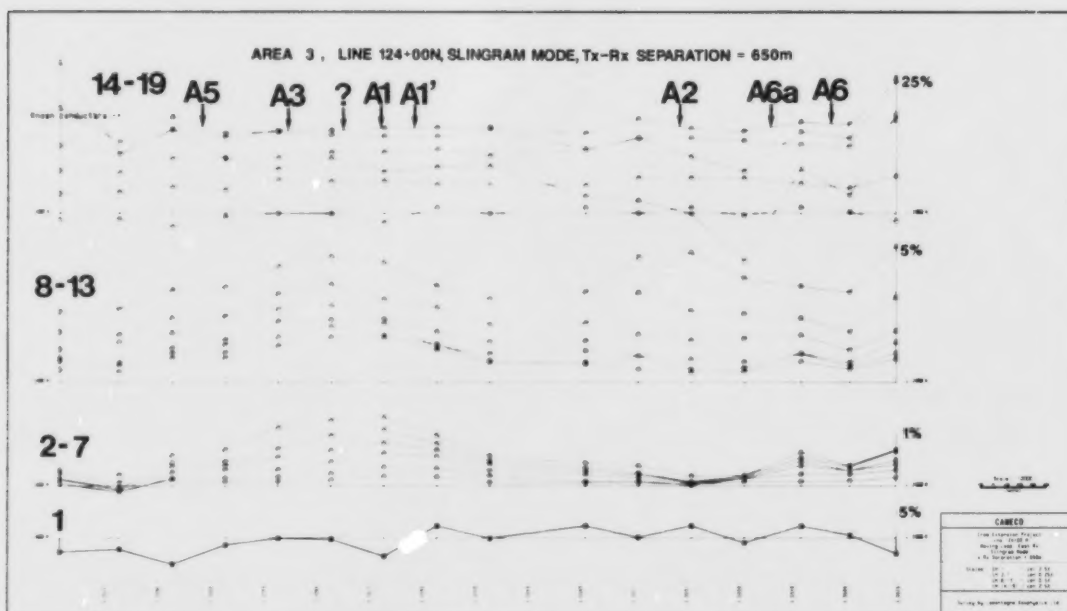


Figure 15 - Area 3, Slingshot mode presentation of UTEM stepwise moving loop data, vertical component, with a 650 m transmitter-receiver separation.

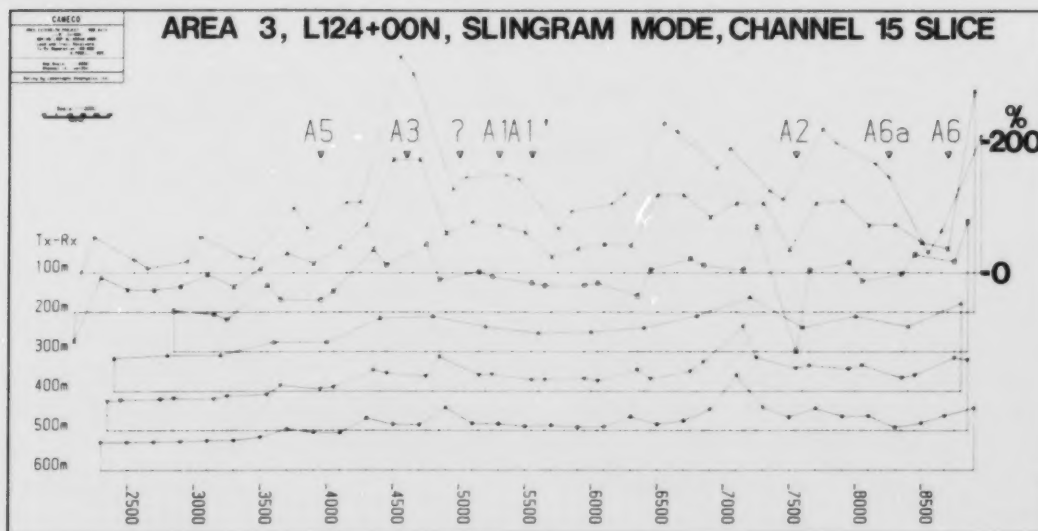


Figure 16 - Area 3, Slingshot mode presentation of a channel 15 slice of vertical component UTEM3 stepwise moving loop data for transmitter receiver separations from 100 to 600 m, line 124+00N.

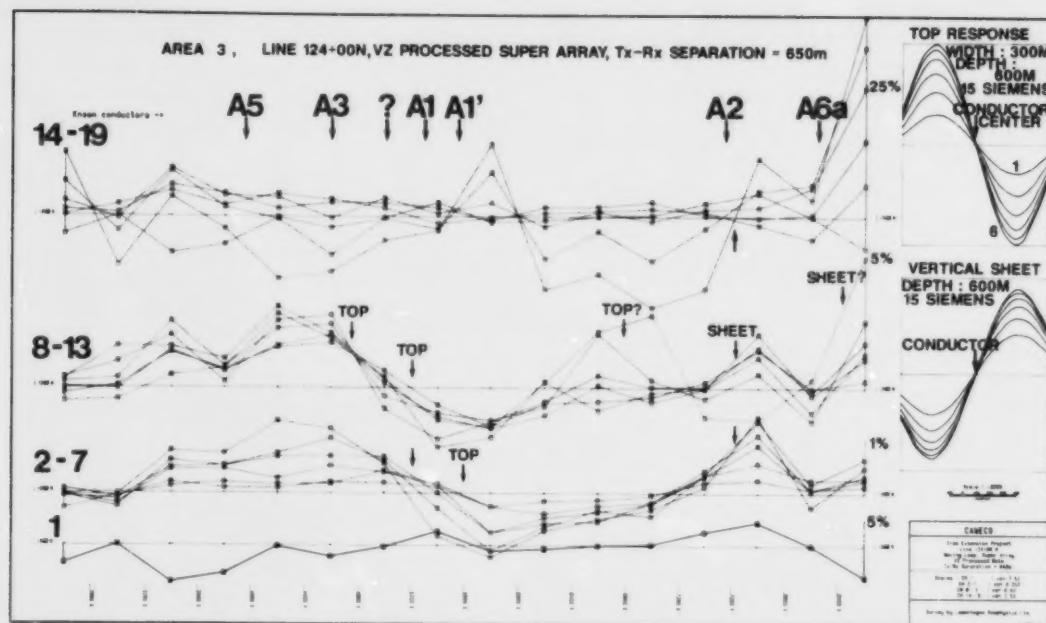


Figure 17 - Area 3, VZ processed stepwise moving loop data, vertical component, with a 650 m transmitter - receiver separation.

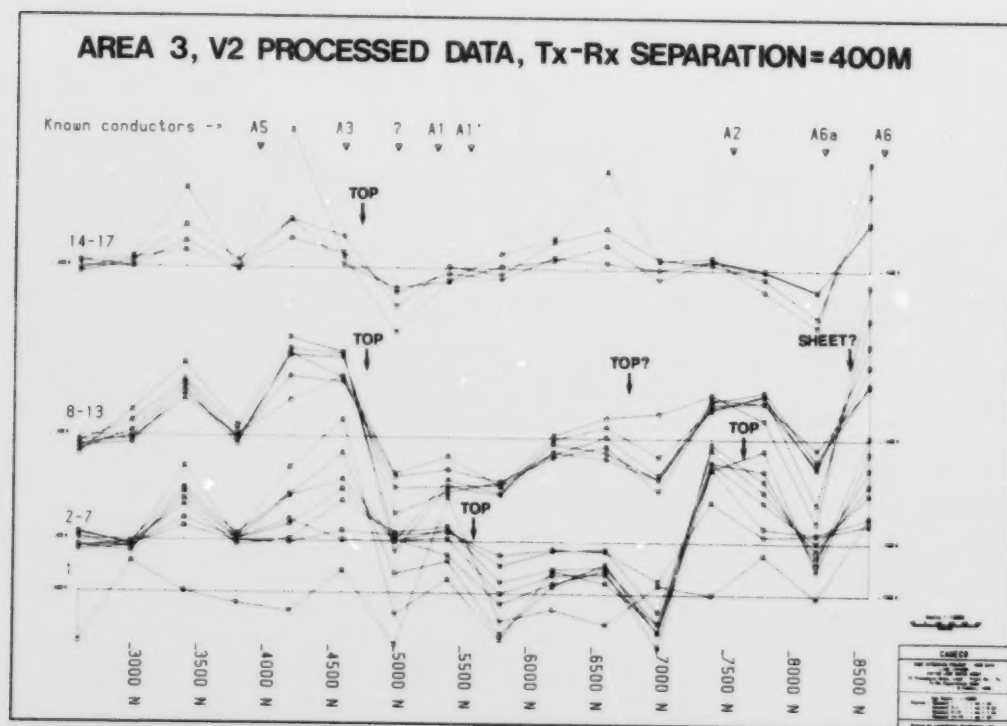


Figure 18 - Area 3, VZ processed stepwise moving loop data, vertical component, with a 400 m transmitter - receiver separation.

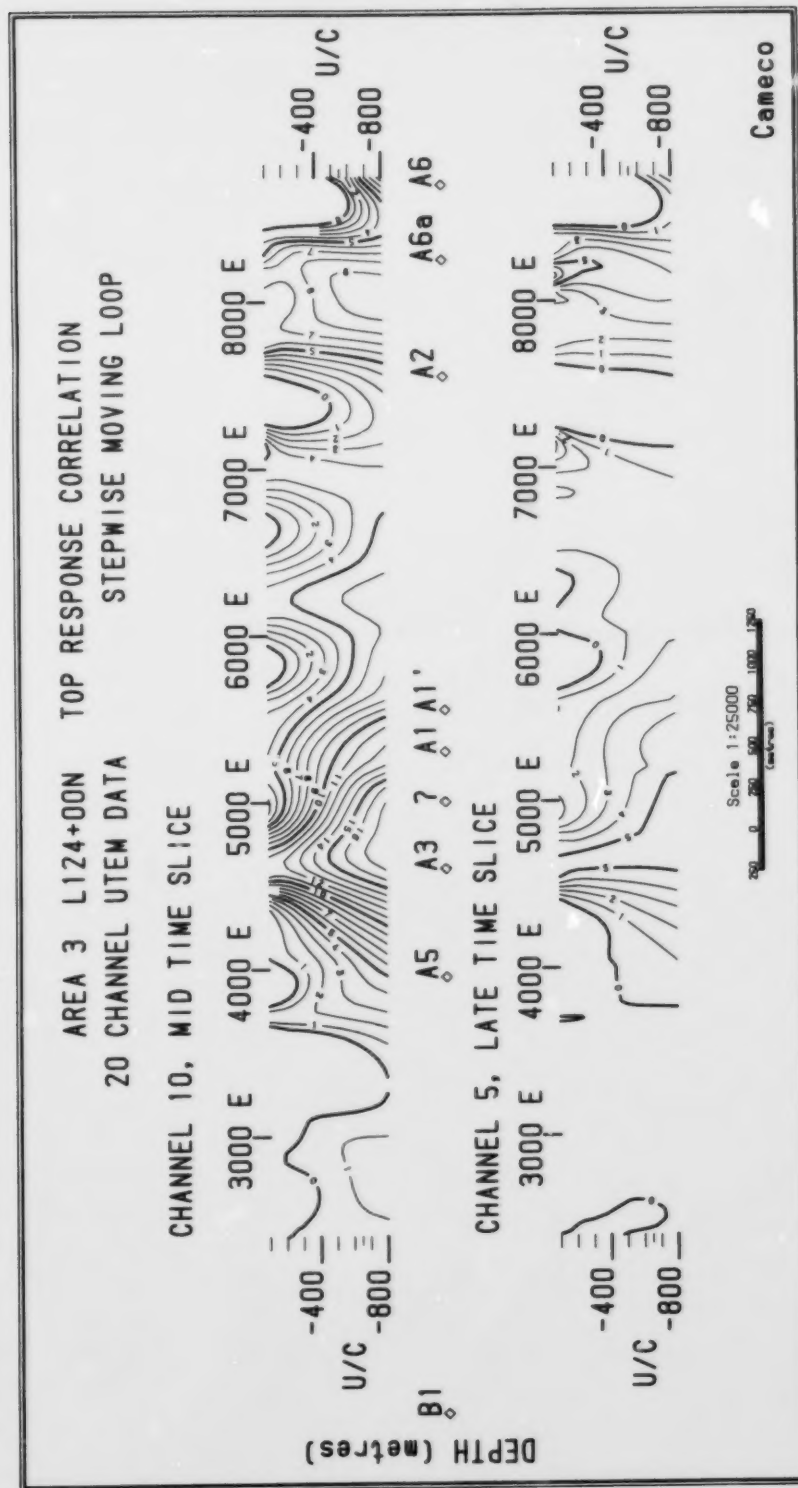


Figure 19 - Area 3, imaged sections of top response correlation of stepwise moving loop data to a depth of 800 m for channels 5 and 10, line 124+00N.

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GLACIAL BOULDER LITHOGEOCHEMISTRY: AN EFFECTIVE NEW URANIUM EXPLORATION TECHNIQUE IN THE ATHABASCA BASIN, SASKATCHEWAN

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ABSTRACT

Recent studies of hydrothermal alteration around uranium mineralization in the eastern Athabasca Basin have shown that the deposits have distinctive geochemical signatures, which extend upward to the subcrop, in some cases through hundreds of metres of sandstone. Definition of such sandstone halos is now an integral part of deep drilling programs. Shallow drilling has been tested as a technique to delineate lithogeochemical anomalies in subcrop, however, coverage has been limited due to costs, especially in areas covered by several tens of metres of glacial overburden.

Orientation studies by Uranerz (1986) and Cameco (1987), were carried out in two areas of known mineralization to determine if these subcrop halos could be detected in glacial boulders. The results were very encouraging since lithogeochemical anomalies in boulders were almost as strong as those in the subcrop. The down-ice dispersion trains in the study areas start less than a few hundred metres from the bedrock source.

Since 1987, several thousand boulder samples have been collected on various exploration projects, and the initial encouraging results have been confirmed. The data have been used to define alteration halos associated with U mineralization and to outline regional alteration trends. The technique is effective because boulder sampling is rapid and inexpensive compared to most other exploration methods used in this environment.

Sampling and analytical techniques are described. Regional lithogeochemical patterns defined by boulders are shown, and boulder lithogeochemical distributions are compared with drilling results in mineralized zones on the Read Lake property (Uranerz Exploration and Mining), the McArthur River property (CAMECO), and other areas. These results have established boulder lithogeochemistry as an important uranium exploration technique in the Athabasca Basin.

INTRODUCTION

The Athabasca Basin of northern Saskatchewan, has been the focus of exploration for Paleo-Helikian unconformity-type uranium deposits for the past two decades (Figure 1). Early exploration was spread over much of the basin, although particular attention was directed towards the thinner portions of the sandstone around the perimeter. The discovery of several world class uranium deposits in the southeastern part of the basin (e.g. Rabbit Lake, Collins Bay, Key Lake, Midwest Lake, Cigar Lake) has resulted in exploration efforts being concentrated in this area.

An effective new uranium exploration technique is described in this paper. The method combines

aspects of glacial geology and lithogeochemistry in context with our current understanding of unconformity-type uranium deposits.

General Bedrock Geology

The Athabasca Basin consists of shallow dipping quartz sandstones and conglomerates of the Athabasca Group, which have been subdivided into several formations based on their depositional history (Ramaekers, 1983). These sediments fill an oval-shaped basin with present thicknesses in the order of 1500 m in the centre of the basin. These rocks once covered a much wider area; present day outliers occur up to 75 km away from the basin. The Athabasca Group unconformably overlies a Hudsonian deformed basement of Archean and Aphebian

metasedimentary, metavolcanic and plutonic rocks (Tremblay, 1982, Langford, 1986). The southeastern portion of the Athabasca Basin is underlain predominantly by the Wollaston Domain and the eastern edge of the Mudjatik Domain. The Wollaston Domain comprises an Aphebian supracrustal sequence called the Wollaston Group (Ray, 1975) overlying remobilized Archean basement which is situated in the cores of doubly-plunging domal inliers (Sibbald, 1983). The lithostructural Mudjatik Domain consists predominantly of granitoid gneisses containing discontinuous arcuate basins of Aphebian supracrustal rocks (Lewry and Sibbald, 1980).

Athabasca Basin Unconformity-type Uranium Deposits

The majority of economic and sub-economic uranium deposits of the Athabasca area are located in the southeastern portion of the basin, and are associated with basal Wollaston Group graphitic gneisses. This high potential corridor lies in a 20 to 30 km wide northeast-trending zone that broadly defines the western margin of the Wollaston Domain. The uranium deposits have been described by numerous authors;

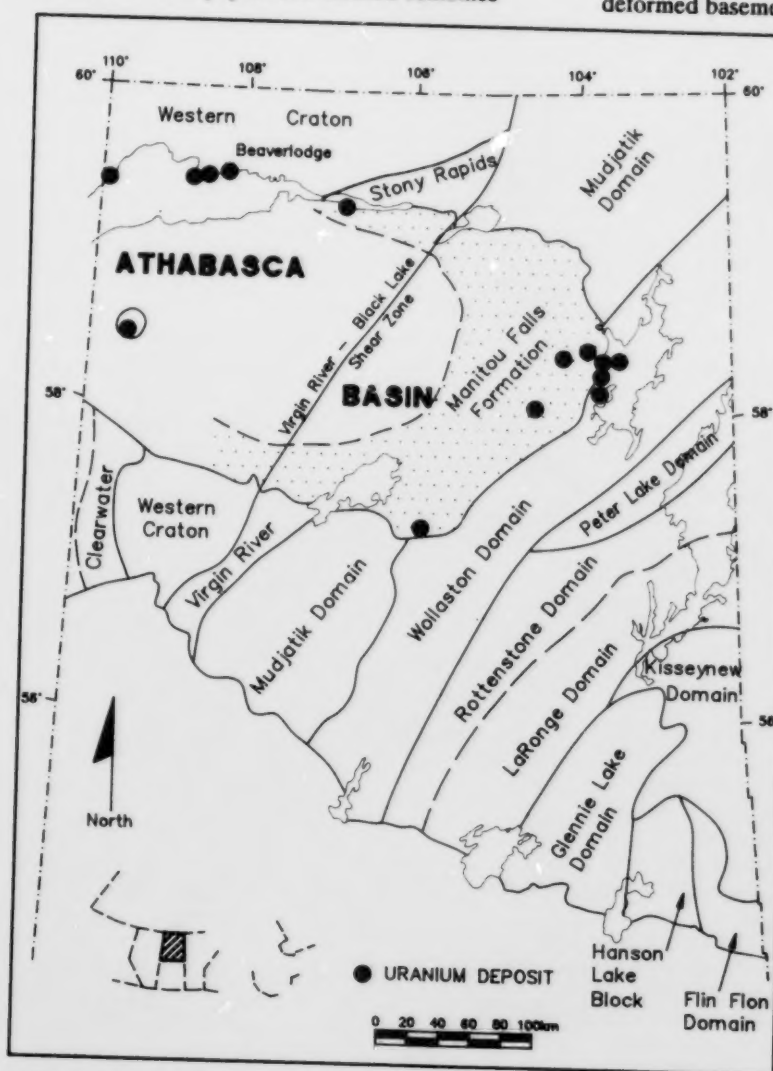


Figure 1 - Regional geology of northern Saskatchewan and locations of uranium deposits.

excellent summaries include Sibbald and Petruk (1985), Tremblay (1982), Cameron (1983) and Evans (1986).

Athabasca Basin unconformity-type uranium deposits (Figure 2) share many characteristics, although not all features are necessarily present in an individual deposit. These include the presence of, or proximity to:

- 1) the Athabasca Group, and more specifically the interbedded quartz sandstones and conglomeratic sandstones of the Manitou Falls Formation,
- 2) the pre-Athabasca unconformity,
- 3) basal Aphebian graphitic lithologies within the western margin of the Wollaston Domain,
- 4) intra-Aphebian unconformities,
- 5) Aphebian mylonite horizons within or adjacent to graphitic lithologies,
- 6) strike and cross faults, especially those with pre- and post-Athabasca reverse components,
- 7) local basement topographic highs, and
- 8) fractured or friable Athabasca Group and basement rocks with lithogeochemical alteration halos.

Alteration halos associated with these deposits have been described by Sopuck *et al.* (1983), Hoeve (1984), and Earle and Sopuck (1989). Basement lithogeochemical anomalies locally extend several

hundred metres beyond the ore as at Key Lake (Ruhmann, 1987) and Cigar Lake (Fouques *et al.*, 1986, and Bruneton, 1987). A complex series of mineralized and unmineralized hydrothermal stages is recognized in most of these deposits (Ruhmann and Von Pechmann, 1987, 1989, Hubregtse and Sopuck, 1989).

The regional geochemistry and clay mineralogy of the Manitou Falls Formation in the eastern part of the basin are discussed by Earle and Sopuck (1989). The sandstone is remarkably mature, and has a consistently low geochemical background over a large area. The rocks consist almost entirely of quartz grains with 1 to 10% of the rock composed of varying proportions of kaolinite, illite and chlorite. In most areas, kaolinite is the dominant clay mineral (Figure 3) whereas chlorite is rare. Within twenty metres of the sub-Athabasca unconformity, however, illite is generally dominant over kaolinite, and chlorite levels increase to several tens percent of the 'clay' fraction.

In the southeastern part of the basin there is a 10 to 40 km wide region, extending over 100 km northeast from Key Lake, in which illite is dominant over kaolinite (Figure 3). This 'regional illite anomaly' circumscribes all known uranium mineralization in the area, including Key Lake and the P2 area at McArthur River. The mineralized zones, however,

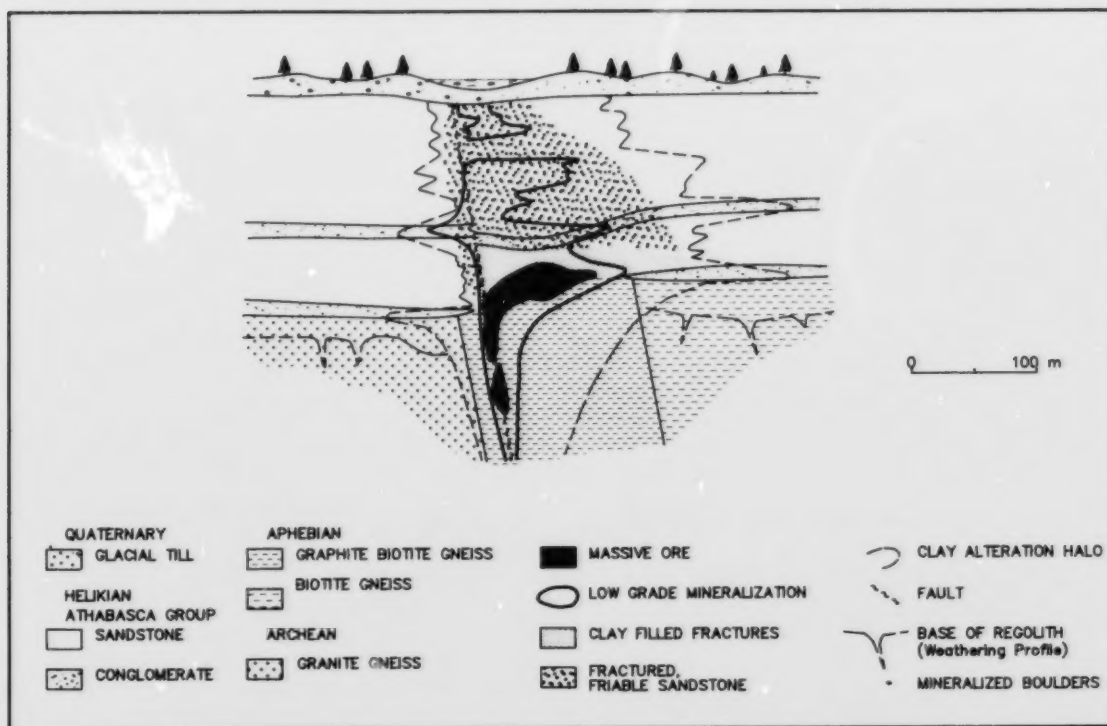


Figure 2 - Idealized cross-section of an Athabasca Basin unconformity-type uranium deposit.



Figure 3 - Regional distribution of illite in sandstone of the eastern Athabasca Basin.

are characterized by local kaolinite halos. Mineralization at Key Lake is associated with a several hundred metre wide kaolinite anomaly (Figure 4). The clay halos are associated with weak uranium and lead anomalies (less than 3 ppm) which can extend to surface through as much as 500 m of sandstone. Boron enrichment is common with concentrations commonly exceeding 1000 ppm, compared to a 20 ppm background. The boron halos are generally the most conspicuous features around the mineralized zones (e.g. Key Lake, Figure 4). Chlorite enrichment of the middle and upper sandstone is also common around mineralization in the southern areas. Chlorite may compose up to 50% of the matrix of the sandstone, compared to virtually nil in background areas. Another important feature of the alteration chimneys in the McArthur-Read Lake area is that the sandstone is generally silicified. The upper sandstone clay content in this area is reduced from the background of around 2% to less than 1%.

North of the regional illite anomaly, mineralized zones such as Midwest Lake and Cigar Lake are characterized by prominent illite chimneys in a kaolinitic background. The chimneys are up to several hundred metres wide and extend upwards to

the subcrop. The illitic chimney over Midwest Lake is shown in Figure 5 and the regional distribution of such illite anomalies with respect to uranium mineralization is shown on Figure 3.

These northern mineralized zones are also characterized by sandstone uranium anomalies, extending upwards to the subcrop, with concentrations between 3 and 10 times the 1 ppm background, and similar but less intense lead anomalies. There is commonly some boron enrichment above these mineralized zones, but the anomalies do not generally extend for more than 100 m above mineralization.

Glacial Geology

Continental glaciers have advanced and retreated across northern Sas-

katchewan during the Quaternary, with the last retreat being approximately 8000 years ago. The Athabasca Basin is almost entirely mantled by glacial deposits that comprise predominantly ground moraine, glaciofluvial outwash and glaciolacustrine deposits (Schreiner, 1984).

Glacial features in the eastern part of the basin indicate ice movement was to the southwest (ca 225°). The area is marked by extensive development of drumlinoid features, which can exceed 100 m thickness at their crests, whereas the ground moraine is commonly 10-20 m thick in the low-lying regions. These deposits have been classified as sandy to very sandy tills (Schreiner, 1984) and can contain up to 25% cobbles and boulders. In the eastern part of the basin over 90% of the cobbles and boulders are derived from Athabasca Group sandstones.

Outwash sand and eskers represent a relatively minor component of the glacial deposits in the exploration area. Outwash sands occur in low areas between drumlins and are associated with local eskers. Outcrop exposures and felsenmeer comprise less than 1% of the surface area.

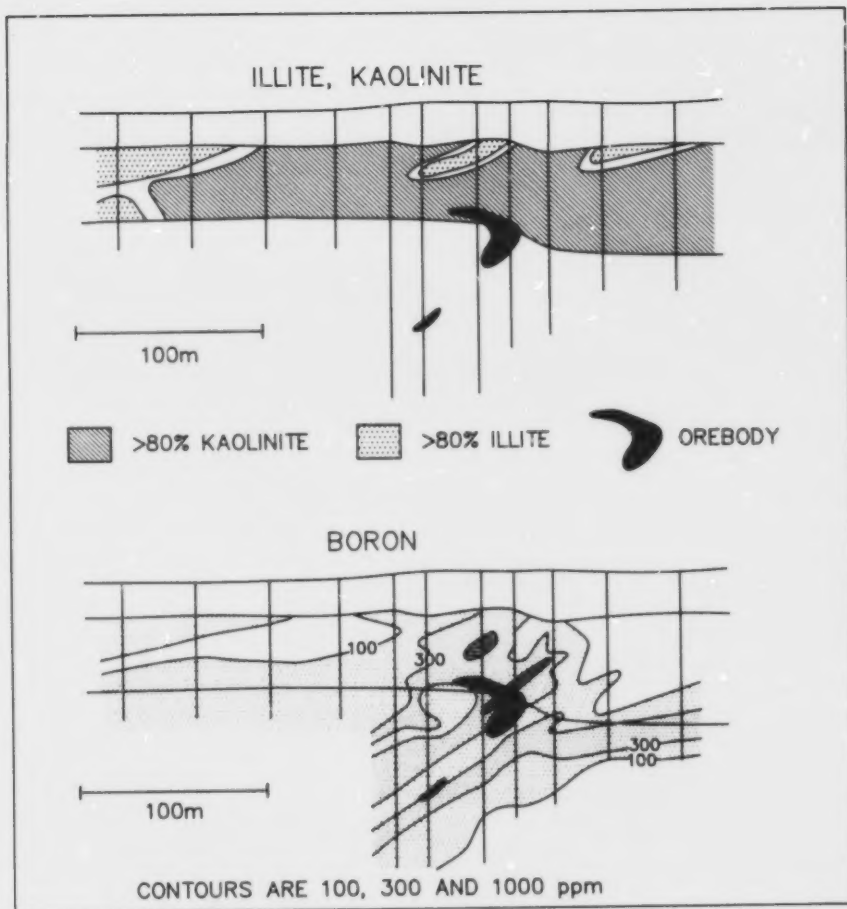


Figure 4 - Illite, kaolinite and boron distributions in the sandstone above the Deilmann Deposit, Key Lake.

Historical Significance of Boulder Trains in the Athabasca Basin

The presence of radioactive boulder trains has played a major role in the exploration history of several Athabasca Basin uranium deposits and prospects. Ground follow-up of airborne radiometric anomalies led to the discovery of radioactive boulders in the glacial till. Tracking of these boulder trains, together with ground geophysical surveys, have contributed to successful diamond drill programs.

In 1968, ground follow-up of airborne radiometric anomalies delineated a boulder train that led to the discovery of the Rabbit Lake deposit later that same year (Heine, 1986). Similarly, radioactive pebbles were found in the vicinity of the Cluff D zone (Laine, 1986), and in 1971 high-grade uranium-nickel bearing boulders were found 5 km south of the Key Lake deposits (Dahlkamp and Tan, 1977). These near-sur-

face deposits produced radioactive boulder trains as a result of the glacial erosion of the upper portion of the orebodies themselves.

Radioactive boulder trains have also been discovered in areas of thick Athabasca sandstone. The Midwest Lake deposit, overlain by 200 m of sandstone, produced a boulder train which can be traced for over three kilometres (Scott, 1981). The Read Lake and BJ Lake showings occur at even greater depths, and both have associated glacially transported radioactive boulder trains. Dravite-bearing non-radioactive boulders can also be traced to the BJ Lake area on the McArthur River property (Ramaekers *et al.*, 1982).

The success of these projects led to extensive and systematic programs of ground scintillometer prospecting over much of the Athabasca Basin and surrounding areas, but with few subsequent suc-

cesses. The obvious conclusion from these results is that the majority of the relatively easily detectable radioactive boulder trains have been discovered.

Development of the Boulder Lithogeochemical Method

Faced with the problem of drilling numerous conductors on its exploration properties in the deep (greater than 500 m) Athabasca Basin environment, Uranerz examined various ways of prioritizing conductive targets. One obvious method of upgrading conductive targets was to explore for the large and conspicuous alteration halos associated with unconformity-type deposits (Sopuck *et al.*, 1983, Hoeve, 1984, Ruhrmann, 1987, Fouques *et al.*, 1986, Clark, 1987). Shallow drilling methods had been employed to locally test the subcrop, but Uranerz wanted to develop a less expensive, reconnaissance approach.

Utilizing its experience in exploring in glaciated terrain throughout Canada, Uranerz completed an orientation survey in 1986 across the previously known Read Lake radioactive glacial dispersion train. The initial composite boulder sampling consisted of a test profile across the dispersion train approximately 1 km down ice from the subcropping mineralization (Figure 6). Composite chip samples of the Athabasca Group Manitou Falls Formation (MFd member) were collected from a minimum of 10 boulders at 100 m intervals. The samples were subsequently analyzed for 29 elements, and XRD clay determinations were done.

Uranium displayed an excellent correlation with the radioactive boulder train, whereas MgO and vanadium showed much broader anomalies (Figure 7). Both B and Pb had anomalies that were displaced up to several hundred metres north of the radioactive boulder train (Figure 8). Results of the clay determinations showed an excellent correlation of chlorite with the known radioactive boulder train (Figure 9). Based on these initial positive results, composite boulder sampling was expanded in 1987 and 1988.

Orientation studies were independently carried out in 1987 by Cameco (then SMDC) on its adjoining

McArthur River project. Boulder and fine fractions of the till were analyzed and strong anomalies were observed adjacent to a zone of mineralization. The boulders clearly provided a more conspicuous anomaly than the fine fraction of the till (Figure 10). The large angular boulders, common throughout the Athabasca Basin, are more representative of local bedrock than the finer till material which surrounds them, presumably because the finer material has travelled farther.

SAMPLING PROCEDURES

The composite Athabasca Group sandstone boulder sampling procedures described here were developed specifically to detect glacial dispersion fans associated with economic Athabasca Basin unconformity-type deposits. It was presumed that the subsurface size of a geochemical halo associated with a large economic deposit would be a few hundred metres wide and a kilometre or more long.

Samples are collected from cobbles and boulders in ground moraine, which forms relatively flat undulating topography and, more commonly, drumlin terrains. Large angular boulders are the preferred sample medium since they commonly protrude through moss and sand, and are easiest to sample.

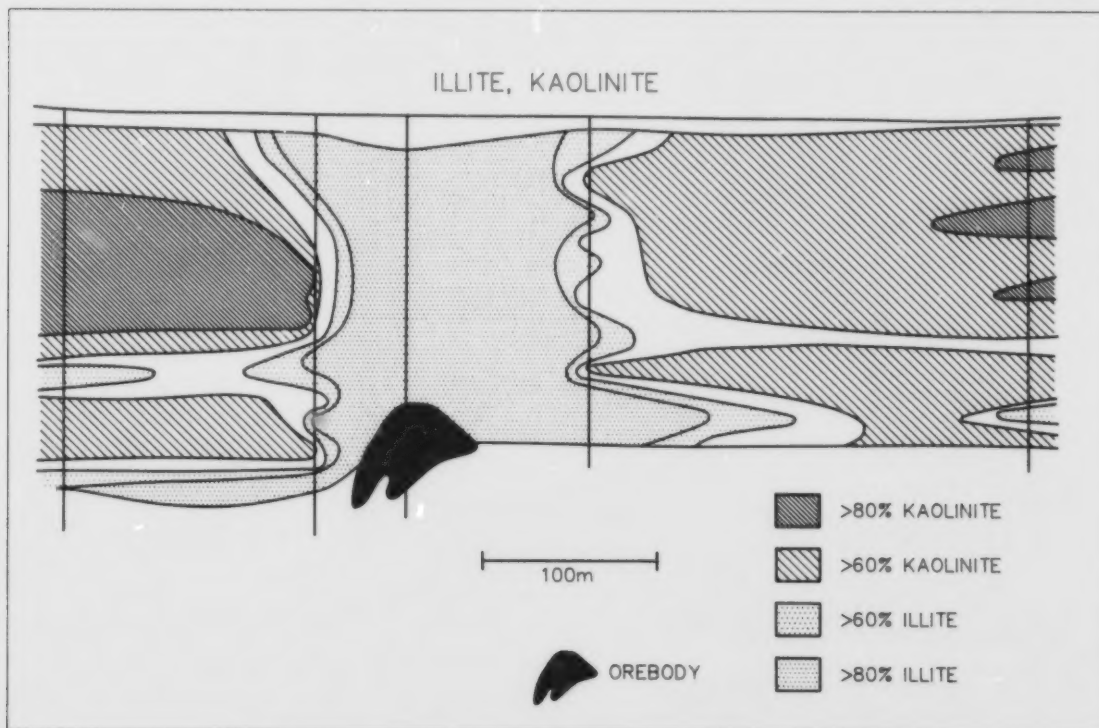


Figure 5 - Illite and kaolinite distributions in the sandstone above the Midwest Deposit.

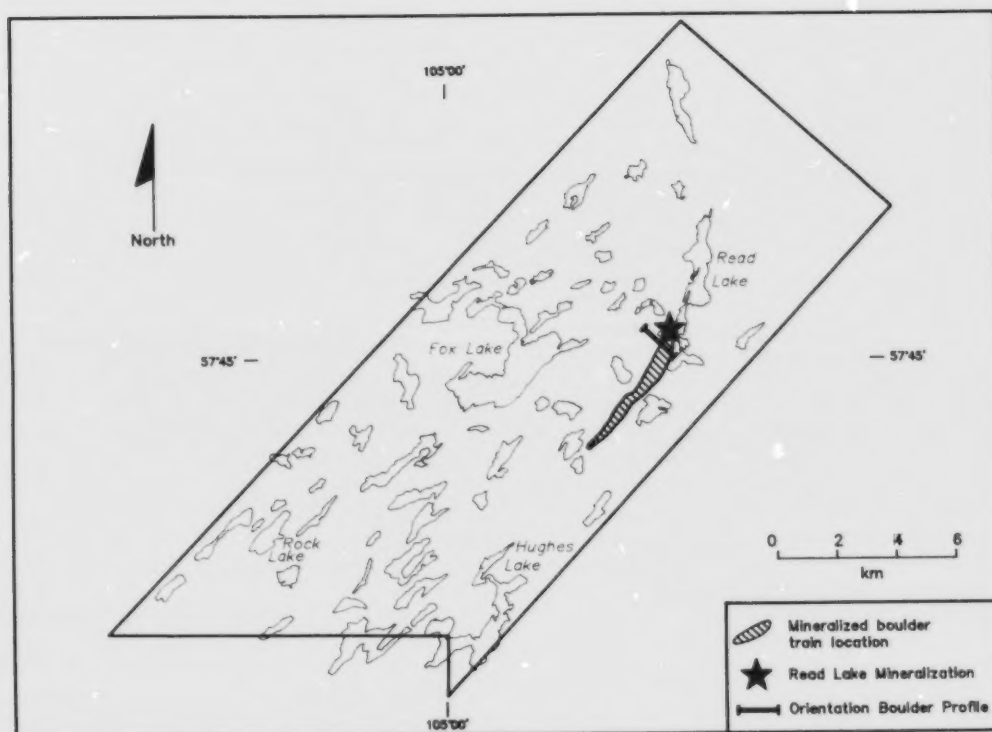


Figure 6 - Read Lake project area, showing locations of the radioactive boulder train and orientation boulder sampling profile.

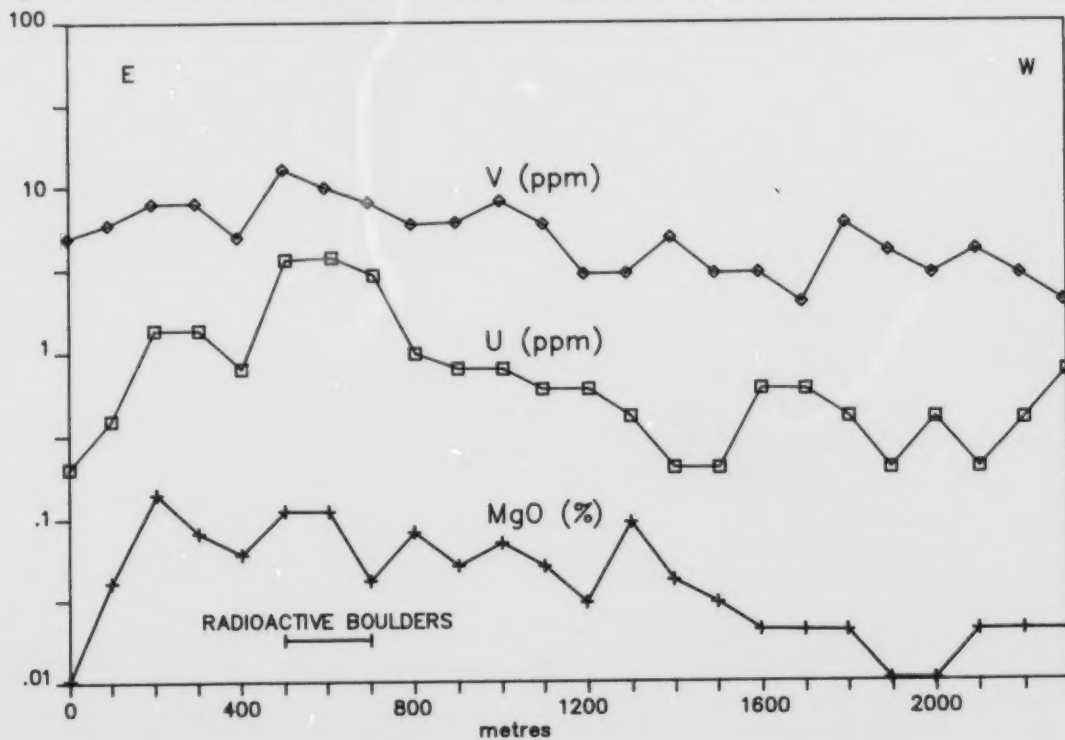


Figure 7 - Distribution of U, MgO and V on the Read Lake orientation boulder sampling profile, 1986.

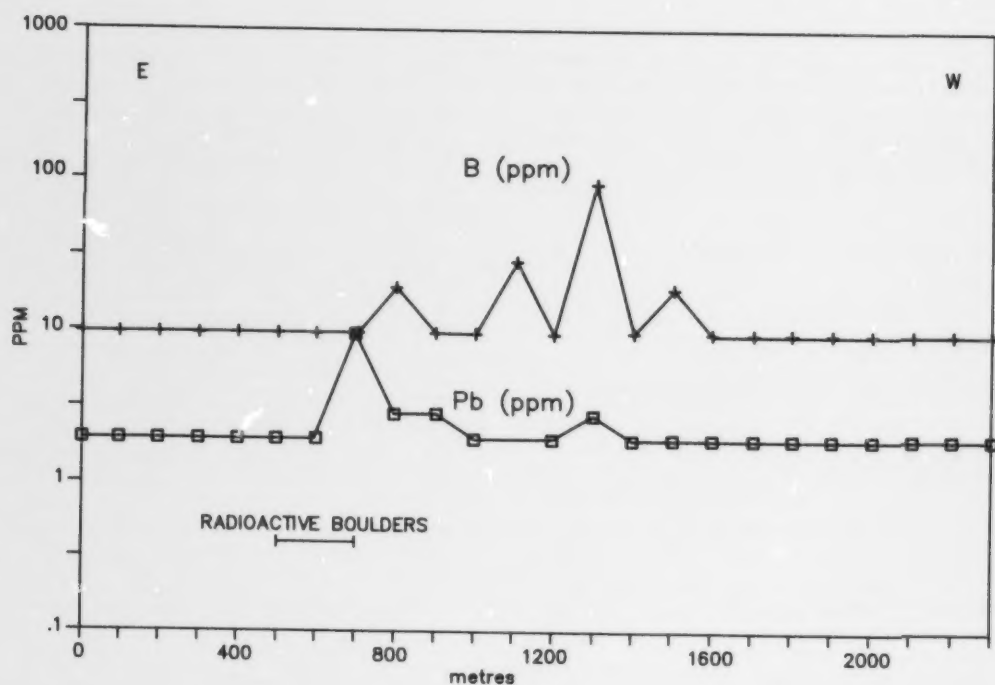


Figure 8 - Distribution of Pb and B on the Read Lake orientation boulder sampling profile, 1986.

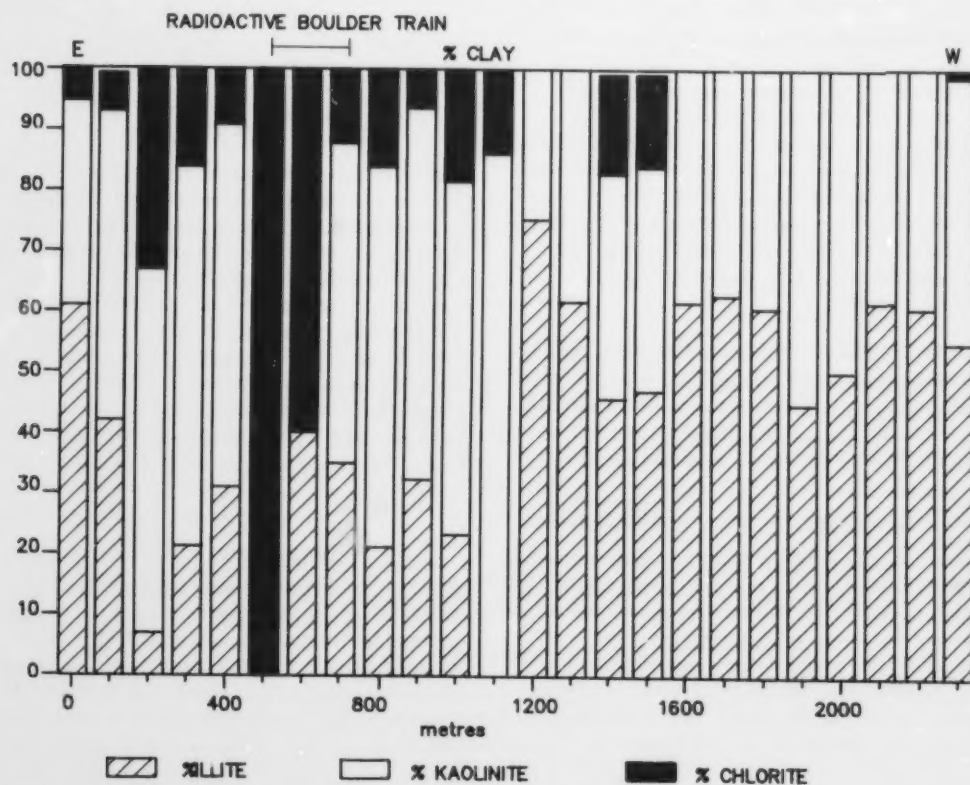


Figure 9 - Distribution of illite, chlorite and kaolinite on the Read Lake orientation boulder sampling profile, 1986.

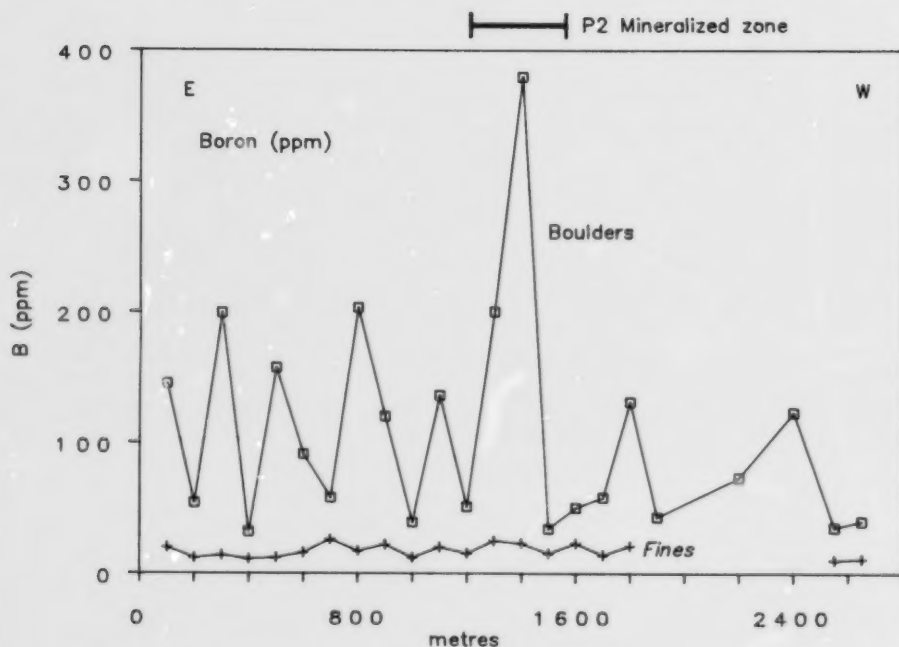


Figure 10 - Distribution of boron in boulders and tills on the P2 area orientation profile - McArthur River Project.

Boulders of basement origins are not sampled, and sandstone boulders not exhibiting lithological characteristics similar to the local subcrop are avoided.

Samples consist of relatively fresh chips, approximately 2 cm³, collected from a minimum of ten boulders within a 10 m radius of the sample station. In addition to recording the sample location and number, notes are also kept on boulder lithology, average boulder size and angularity, glacial geology and topographic position.

Samples are normally collected at 100 m intervals along lines approximately perpendicular to the glacial ice direction. Line spacing varies from 800-2000 m for reconnaissance surveys, to 50 m intervals on lines spaced 300-500 m apart for follow-up surveys.

ANALYSIS AND DATA PROCESSING

Composite boulder samples are crushed and ground, then analyzed for a variety of constituents which enable detection of alteration halos. Trace and major elements are determined by atomic absorption spectrophotometry (AA) and plasma-source emission spectrophotometry (ICP), generally following dissolution in HF, HClO₄ and HNO₃ acids. In most cases uranium is determined by fluorometry.

Data for Al₂O₃, MgO, K₂O and B are used to calculate the proportions of the clay minerals illite,

chlorite and kaolinite in the samples. This clay calculation procedure is based on the premise that the only important Al₂O₃-bearing phases in the Manitou Falls Formation are illite, chlorite, kaolinite and dravite. The technique, which has been described by Earle and Sopuck (1989), has been widely used on uranium exploration projects throughout the basin. The results are comparable to those derived from semi-quantitative x-ray diffraction (XRD) analysis. The advantages of this technique over XRD are that it provides an accurate measure

of the total clay content of the sandstone and does not rely on a physical separation of the clay fraction.

RESULTS

Results from various boulder surveys carried out to date are presented in three sections. Firstly, boulder lithogeochemical data are compared with bedrock lithogeochemical data from an area which has been extensively drilled; secondly, regional lithogeochemical trends are examined; and thirdly, boulder lithogeochemical anomalies associated with uranium mineralization are presented. The results are from five projects in the central part of the eastern Athabasca Basin, situated roughly half way between Key Lake and Cigar Lake; these are Cree-Extension, Epp Lake, Hughes Lake, Read Lake and McArthur River.

Comparison with Bedrock

Many boulder surveys have been conducted over previously drilled areas, making it possible to compare the boulder lithogeochemistry with that of the near-surface bedrock. In most cases there is a close relationship between bedrock and boulders. One example is from a conductive trend on the Cree-Extension Project, which was tested with twenty shallow drill holes in 1987, followed by a boulder sampling program in 1988. The holes were drilled about 20 m into the bedrock at 50 m intervals on lines 800 m

apart. Chip samples were obtained from each core and the average boron value from each hole contoured (Figure 11). The boulder sampling program consisted of 84 composite chip samples at 100 m intervals, also on lines 800 m apart.

The two surveys display similar element distributions, but boron exhibits the strongest anomaly in both cases (Figure 11). Element distributions from the drilling and boulder programs are remarkably similar. There is some evidence of down-ice dispersion in the boulders, although the head of the boulder anomaly is very close to the up-ice end of the bedrock anomaly. Exact definition of the limits of either anomaly is not possible because of the 800 m line spacing.

In this example the overburden is relatively thin (10 to 15 m in most holes). In areas with thicker overburden, a wider interval would be expected between the head of the boulder anomaly and its bedrock source; however, one area with up to 75 m of overburden has an interval of less than 500 m.

Regional Trends

Data from the boulder surveys carried out on the five properties listed above have been combined to contribute some additional information on regional illite and kaolinite patterns in the sandstone of the eastern Athabasca Basin (Figure 12 and cf. Figure 3). These patterns are important because the regional illite anomaly provides a framework for interpreting lithogeochemical data in the area. Within the illitic area all mineralized zones are characterized by

kaolinite-dominant alteration halos and strong boron enrichment.

Within the kaolinitic area all mineralized zones are characterized by illite-dominant alteration halos.

It is important to note that the pattern derived from drill hole data represents the entire sandstone section, whereas that derived from boulders represents only the upper few metres of the sandstone. Nevertheless, the boulder data correspond quite well with the drill hole data. The western limit of the illite zone was not previously defined because of the lack of drill information, but it is now reasonably well defined.

Boulder Anomalies Associated with Uranium Mineralization

Boulder lithogeochemical results from the Read Lake and McArthur River project areas (Figure 12) are discussed in this section. These regional surveys were carried out after the mineralized zones had been discovered by drilling, but were not designed specifically to highlight the known mineralization.

Read Lake Area

Lake sediment sampling and radiometric prospecting by Kerr Addison Mines Ltd., in joint venture with Saskatchewan Mining Development Corporation (now Cameco) led to the discovery in 1980 of a

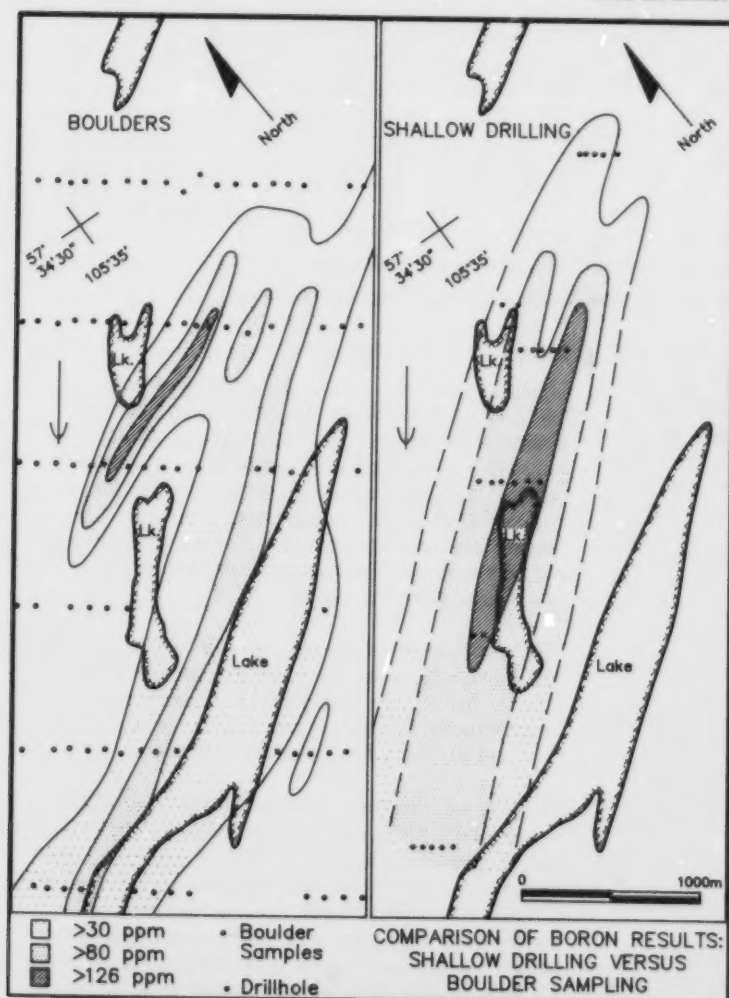


Figure 11 - Boron results in core from shallow drill holes compared with boulders - Cree Extension Project.

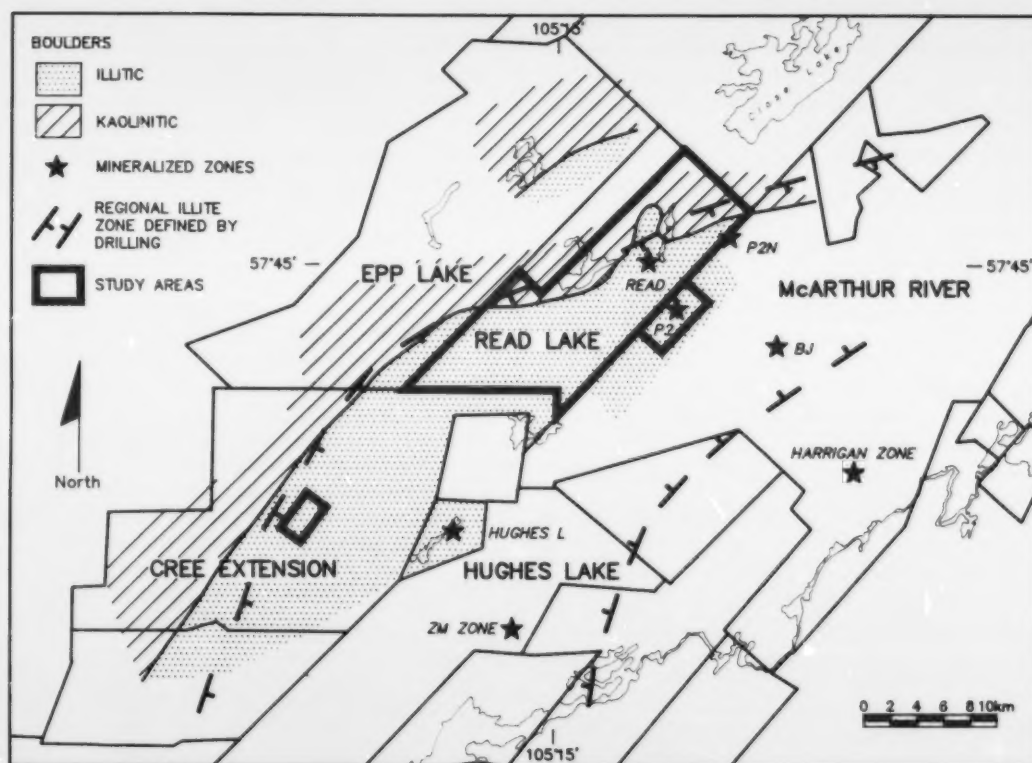


Figure 12 - Regional illite and kaolinite distributions based on boulder results.

radioactive glacial boulder dispersion train at least 5 km long and up to 200 m wide. Subsequent drilling near the head of this dispersion train, near Read Lake, outlined subcropping low grade uranium mineralization in silicified, dravitized and chloritized sandstone. Following an orientation boulder sampling survey by Uranerz in 1986, 750 boulder samples were collected from an 80 km² area. Strong uranium (Figure 13), boron (Figure 14), vanadium (Figure 15), copper (Figure 16), and chlorite (Figure 17) enrichment, along with clay depletion (Figure 18) anomalies are associated with the Read Lake mineralization. The U, V, Cu enrichment and clay depletion anomalies extend at least 6 km down glacial ice direction, whereas anomalous B and chlorite can be traced for at least 13 km. This part of the Read Lake project lies within the regional illite anomaly, and a pronounced kaolinite anomaly is found in boulders down-ice from Read Lake (Figure 19).

Not only was the composite boulder method able to distinguish the known radioactive Read Lake boulder train, but it significantly extended its signature both along strike and across its width. More importantly, from an exploration point of view, several additional targets were outlined. These targets are the focus of current exploration.

McArthur River Area

Uranium mineralization in the P2 area of the McArthur River Project was first discovered by SMDC (now Cameco) in 1985. To date, 24 holes have been completed in the zone with unconformity-related mineralization outlined over a strike length of 600 m. Depth to the unconformity is about 500 m. During 1987 and 1988 boulder surveys were carried out on the P2 grid with sample intervals of 100 m along lines spaced at 600 m.

The area lies within the regional illite anomaly, with the illite background generally greater than 60% (Figure 20). A very strong kaolinite anomaly coincides with the P2 uranium mineralization which lies adjacent to the P2 fault conductor trend.

There is a strongly pronounced boron enrichment along the P2 Fault, particularly just down-ice from the P2 mineralization. Boron concentrations in this area exceed 200 ppm, compared to a background of about 50 ppm (Figure 21). Another subparallel boron anomaly occurs some 300 m southwest of the main P2 anomaly. Chlorite is strongly enriched in the P2 area, as well as up-ice and across strike west of the mineralized zone (Figure 22). In contrast, chloritization is weak in the upper parts of the drill

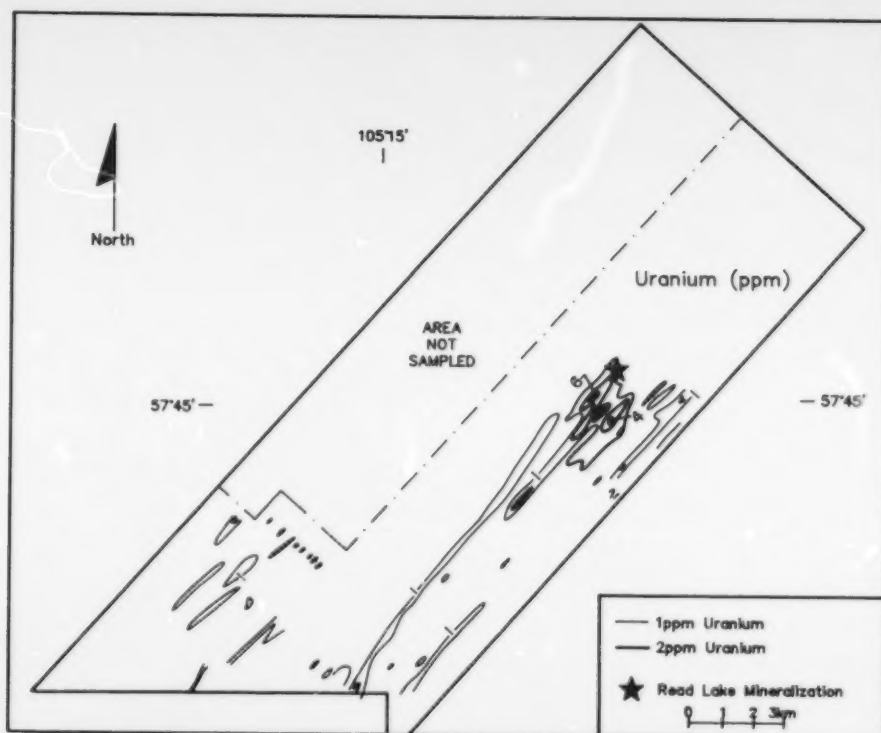


Figure 13 - Distribution of uranium in boulders on the Read Lake property.

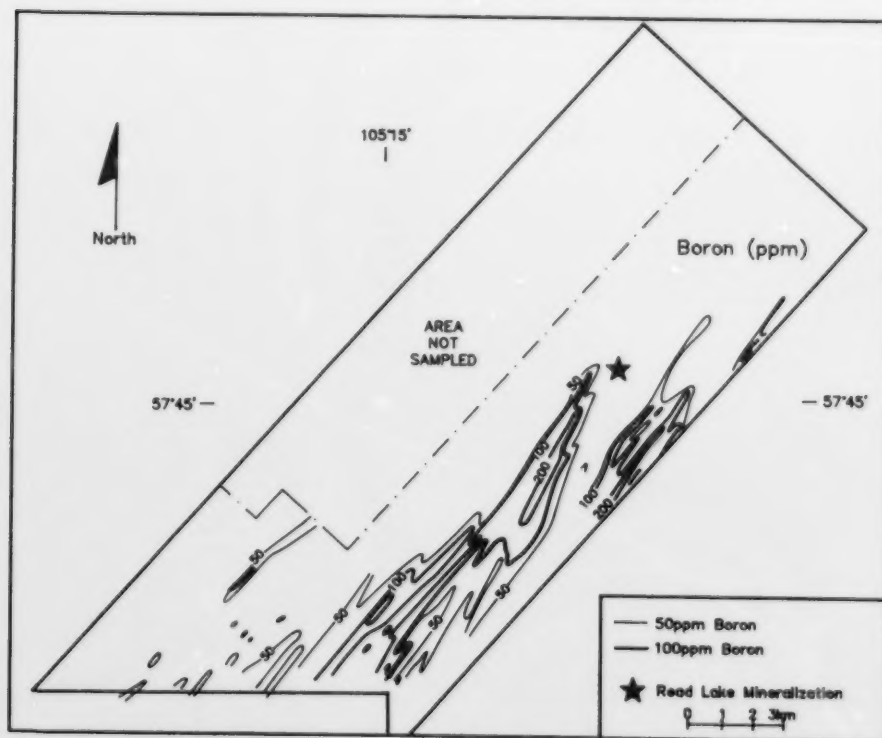


Figure 14 - Distribution of boron in boulders on the Read Lake property.

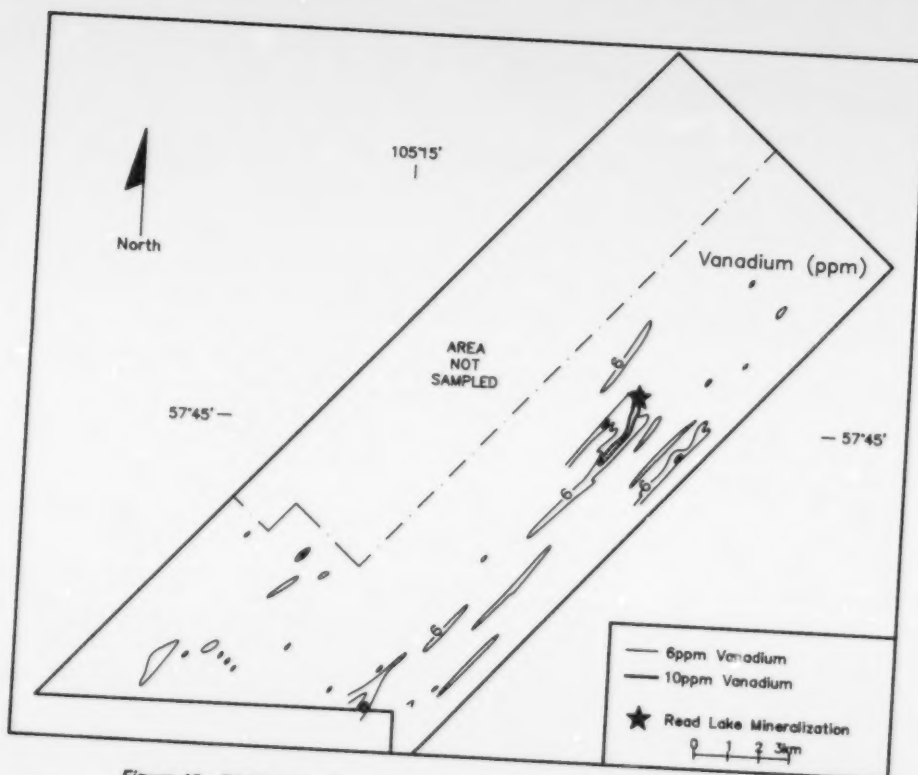


Figure 15 - Distribution of vanadium in boulders on the Read Lake property.

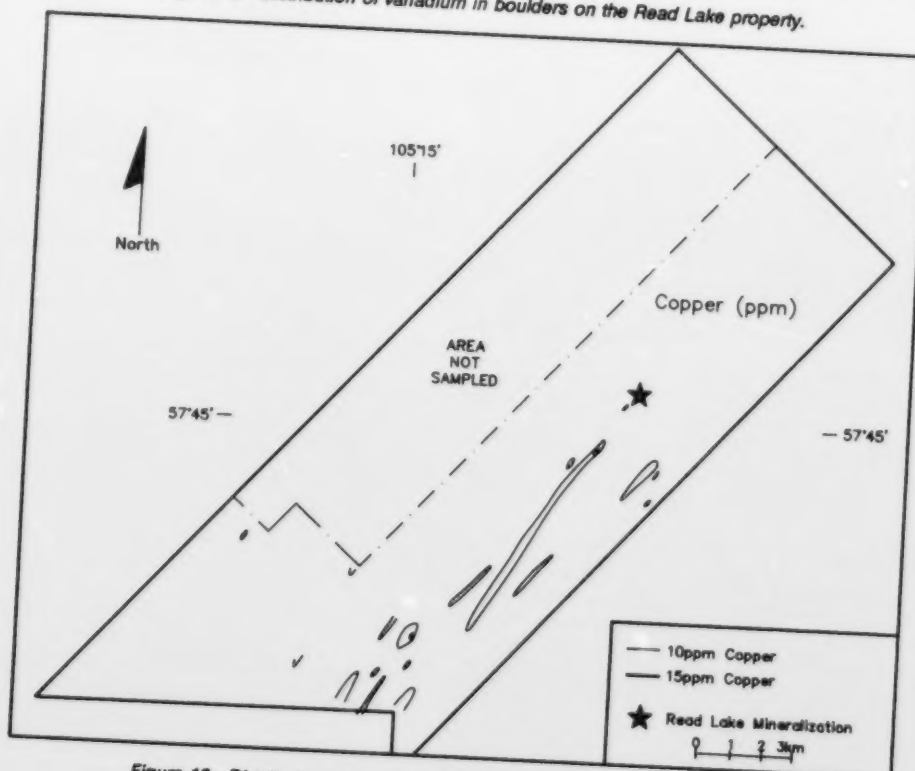


Figure 16 - Distribution of copper in boulders on the Read Lake property.

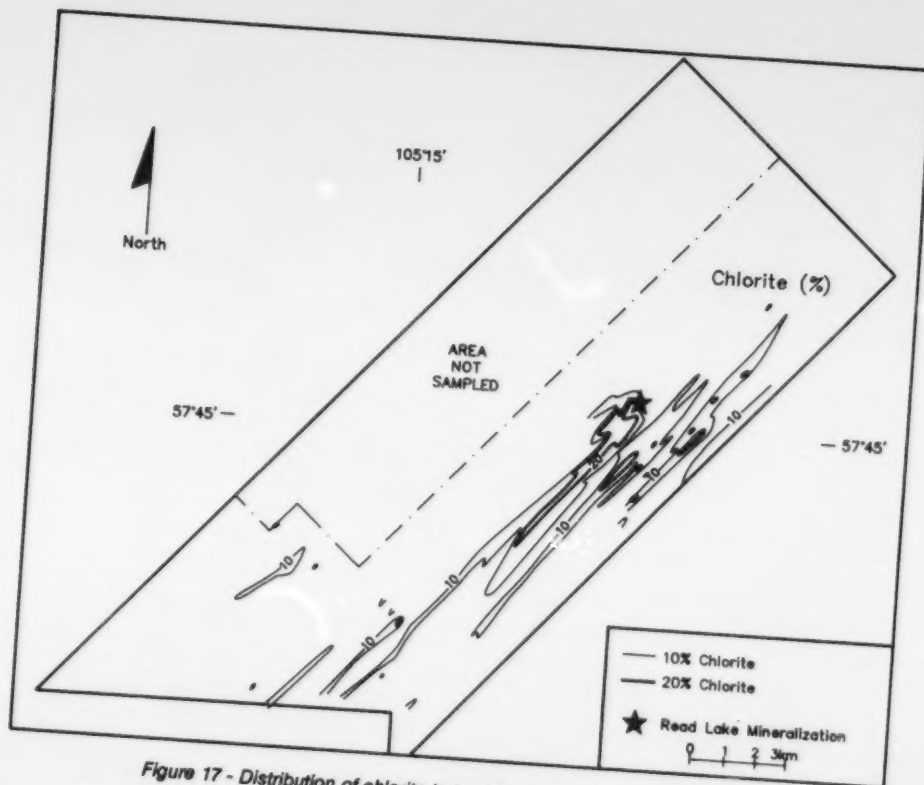


Figure 17 - Distribution of chlorite in boulders on the Read Lake property.

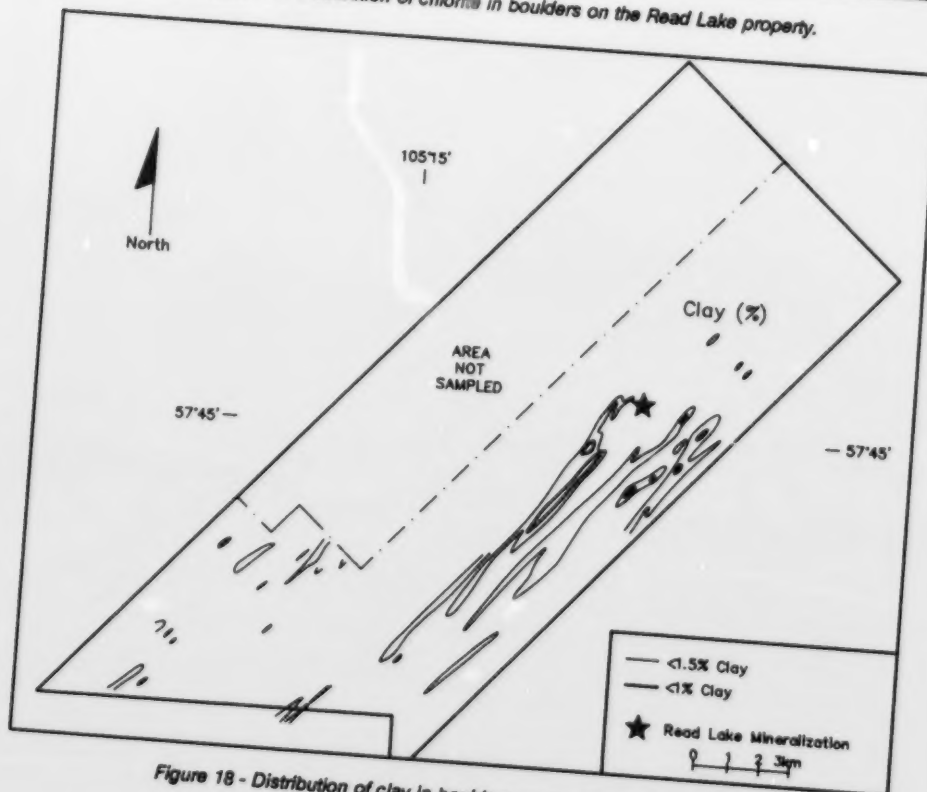


Figure 18 - Distribution of clay in boulders on the Read Lake property.

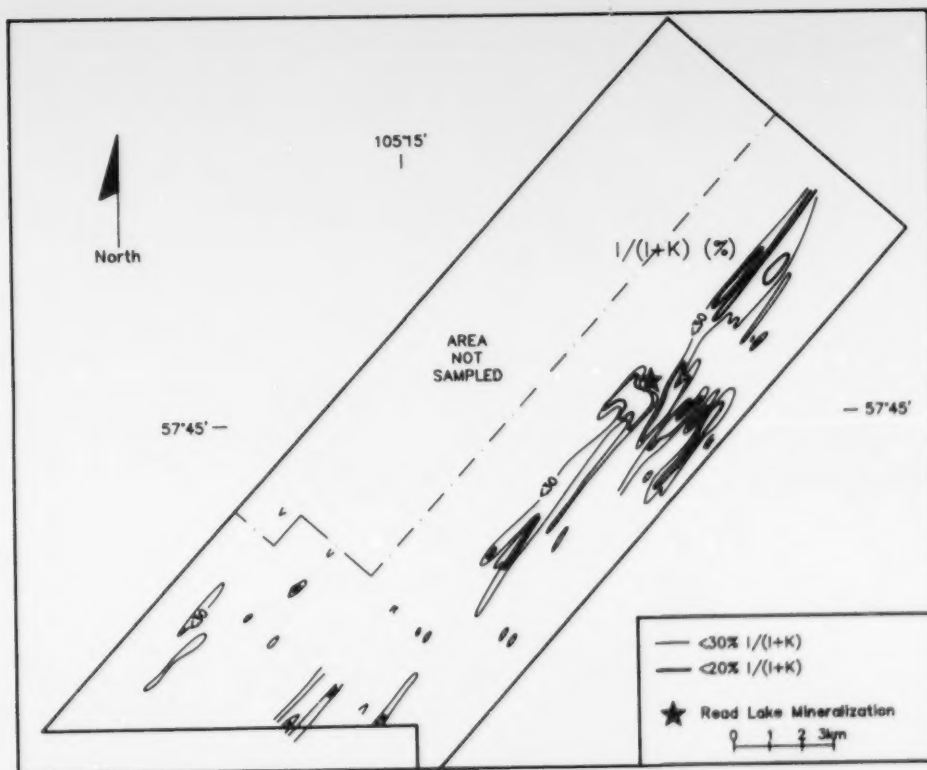


Figure 19 - Distribution of illite and kaolinite (I/I+K) in boulders on the Read Lake property.

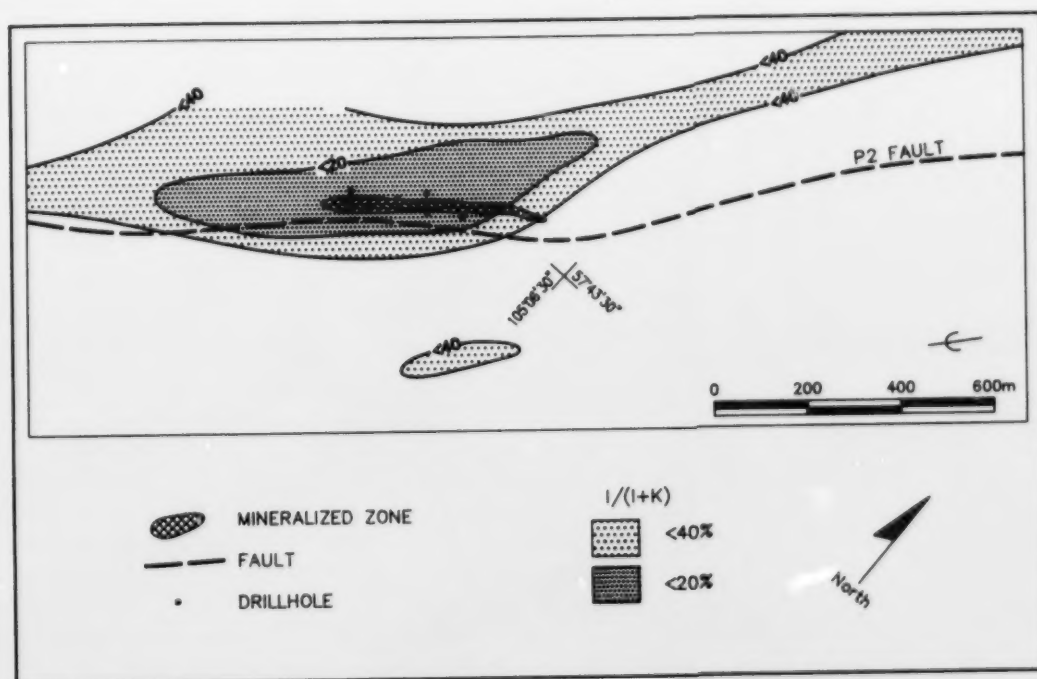


Figure 20 - Distribution of illite and kaolinite (I/I+K) in boulders on the McArthur River property.

holes at P2. A possible explanation is the presence of a peripheral zone of chloritic alteration that extends beyond the existing drill holes, a situation which is noted in other similar mineralized zones. Uranium is slightly enriched along the P2 trend, although a series of untested uranium anomalies occur south and east of the main area of mineralization (Figure 23). Lead, on the other hand, is distinctly enriched in the immediate vicinity of the known mineralization (Figure 24).

DISCUSSION

Effectiveness of the Method

Based on the results presented above it is evident that pronounced lithogeochemical anomalies occur in the subcropping sandstone in the eastern part of the Athabasca Basin, and that these anomalies are also reflected in glacially-transported boulders. Even with till thicknesses of up to 75 m, boulder lithogeochemical anomalies are not far removed from their bedrock source.

The questions that must be resolved are:

1) whether all significant uranium mineralized zones in the region will have alteration halos which reach surface, 2) whether such halos will have been dispersed by glacial processes, and 3) whether all lithogeochemical anomalies are ultimately related to zones of uranium mineralization.

The first question can be addressed by examining mineralized areas. These areas typically have strong lithogeochemical alteration halos, which extend to the subcrop through as much as 500 m of sandstone and exhibit geochemical anomalies with contrasts of four or five times background, extending across a width of at least 100 m. Further into the basin, with sandstone thicknesses of 600 m and more, some of these anomalies may be attenuated, but they will probably still be present and recognizable by reconnaissance scale surveys.

The second question relates to the nature of glacial erosion and the likelihood that there are areas which have not been scoured to the extent that boulders have been picked up and dispersed. Large-scale rock flutings, caused by differential erosion, are observed in other parts of the Shield (Embleton and King, 1975), and such processes may have occurred here as well. If the lateral wavelength of the flutings is less than 200 m, then it is reasonable to expect that at least parts of the alteration halos have been dispersed by the ice.

Examples of lithogeochemical anomalies related to small uneconomic zones of mineralization as well as no known mineralization have been described. The distinction between 'low priority follow-up targets' and 'false anomalies' is not yet clear. Boulder sampling is only one of a range of techniques that can be used for exploration in this area, and none of these is

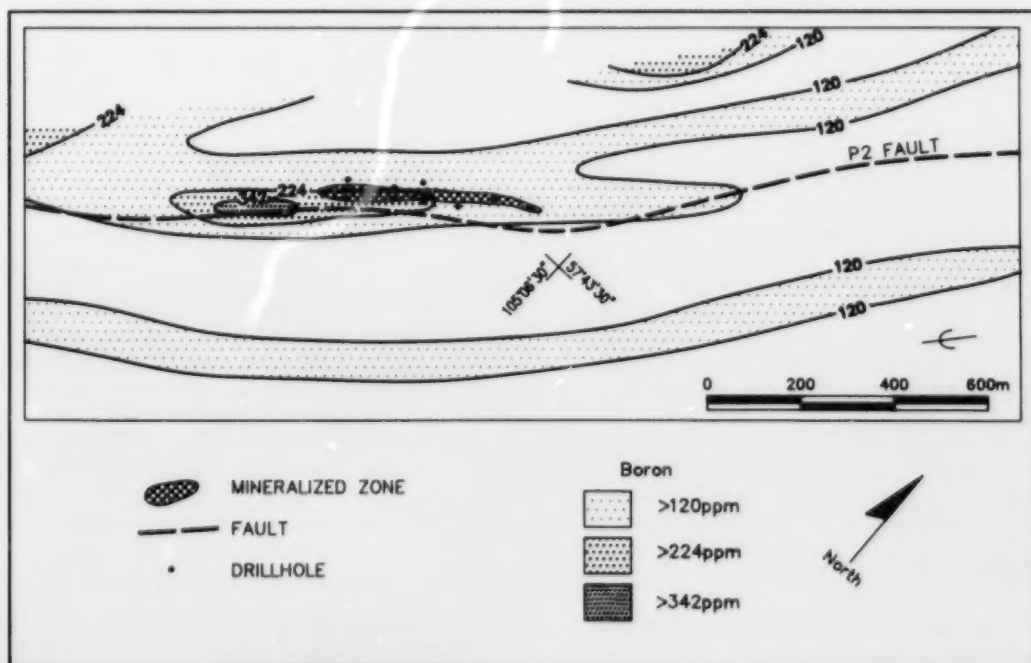


Figure 21 - Distribution of boron in boulders on the McArthur River property.

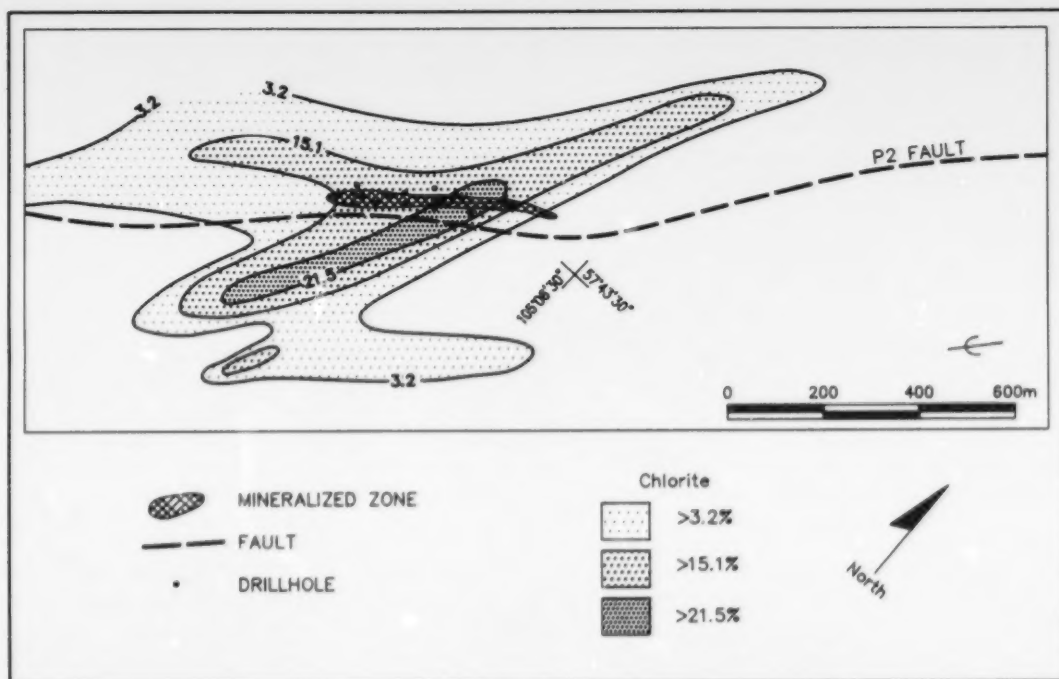


Figure 22 - Distribution of chlorite in boulders on the McArthur River property.

infallible. Electromagnetic surveys have delineated hundreds of kilometres of conductors, most of which are not associated with uranium mineralization.

Sampling Productivity and Costs

As a useful regional exploration tool the boulder sampling technique must allow systematic coverage of a large area in a rapid, yet cost effective, manner. Under ideal conditions utilizing experienced personnel capable of working independently on existing cut lines in an area with suitable boulder till, a daily average of 30 samples per person can be anticipated. Production decreases in areas with low boulder populations, on traverses which intersect bodies of water, and on poor or non-existent grid lines where two person crews are preferred for pace and compass traverses. A regional survey run in 1989 over a portion of the McArthur River project produced an average of 18 samples per man day. The survey was conducted on existing cut lines as well as pace and compass lines with single and two man crews, respectively. A total of 283 samples were collected over a 6 day period on 44 line kilometres of grid. In comparison, on the Read Lake project, 1236 samples were collected on 155 km of existing grid lines averaging 35 samples per man day.

Boulder sampling costs vary significantly depending on whether it is a reconnaissance or follow-up survey, the type of transportation required, the elements

analyzed, the number of samples collected per day and various other factors. The actual cost per sample varies from \$25 to \$60, with the main component of variation being analytical costs.

Item	Cost per Sample
Analysis	\$15 - \$40
Personnel	
(sample collection)	\$4 - \$8
Meals/lodging	\$2 - \$3
Transportation	\$2 - \$5
Data interpretation	\$2 - \$4
TOTAL	\$25 - \$60

Experience has also shown that a sample coverage of 10 samples per square km provides excellent reconnaissance coverage. At \$40 per sample, composite boulder sampling could be completed over a 200 km² property for a total cost in the order of \$80,000 which is equivalent to the cost of one drill hole in the deeper parts of the Athabasca Basin. This survey would not only indicate if an alteration halo extended to surface, but would also identify the type of alteration and the general location of its subcrop.

Follow-up Procedures

A boulder lithogeochemical anomaly outlined in a reconnaissance survey should be followed up with more detailed boulder sampling. Follow-up sampling

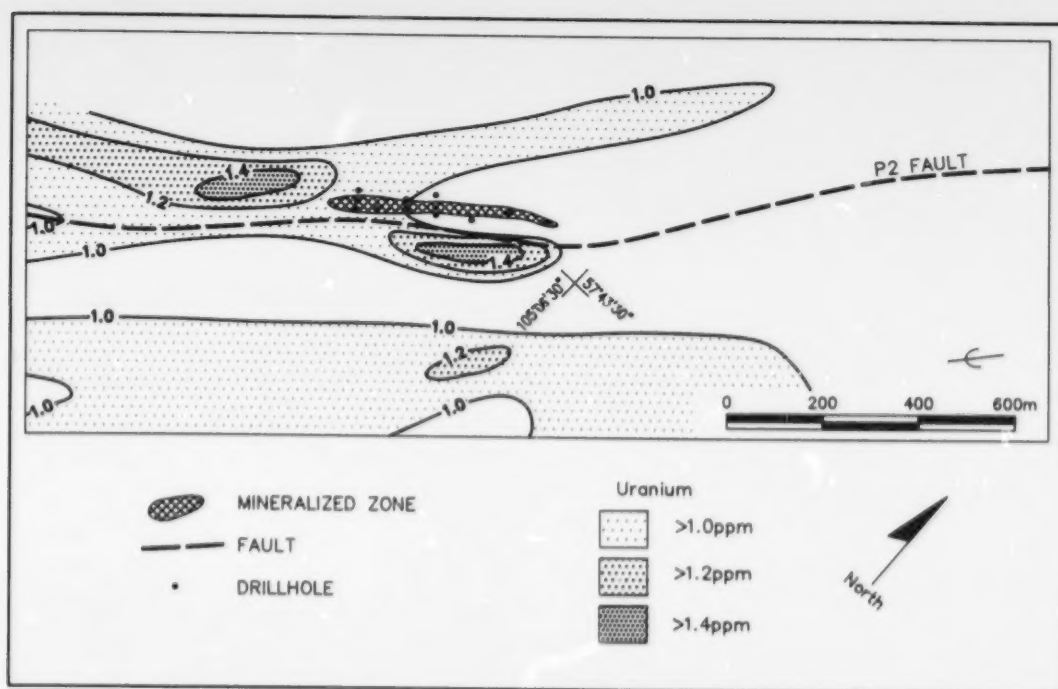


Figure 23 - Distribution of uranium in boulders on the McArthur River property.

density could be as high as 50 m intervals on lines spaced at 300 m to 500 m. Once an anomaly is defined to this extent, the next step is to look carefully at the glacial geology so as to predict the bedrock source of the anomaly, and at the lithology and mineralogy of the anomalous boulders to determine the precise nature of the alteration. Diamond drilling could then proceed, but other information must also be considered, such as the inferred locations of faults and conductors. Drilling programs should be planned with the consideration that there is no certainty that an alteration halo is vertical, and hence that mineralization, if present, may not be located directly beneath the surficial anomaly.

Limitations

The coverage of a boulder survey can be severely restricted by the availability of suitable material. Nevertheless, there are few areas within the eastern part of the Athabasca Basin where some reasonable coverage cannot be achieved. Significant anomalies are generally large enough to be detected even where only a few samples can be collected per square kilometre. In areas of very extensive lakes, swamps or sand plains, one alternative is the slow and expensive option of shallow drilling.

The composite boulder method is based on the premise that recognizable alteration halos associated with Athabasca Basin unconformity-type uranium

orebodies extend to the surface and that these have been eroded by glacial processes, resulting in an anomalous glacial dispersion train recognizable within the cobble/boulder component of the ground moraine. Ground moraine is the dominant glacial deposit over much of the area sampled to date, but it is not always clear to what extent this material is locally derived. Sandstone boulders generally outnumber basement boulders by up to 10 to 1, but locally basement boulders are dominant. In these cases it can only be assumed that the till is partly of distant origin. Fortunately such situations are easily recognized.

Results obtained from areas with known alteration halos are generally consistent despite local variations in till thickness and in the apparent contribution from far-travelled material. Other glacial deposits such as eskers, outwash, and ablation till would undoubtedly redistribute or mask the anomalous glacial dispersion trains. For the most part, these are not significant factors in this exploration area although, in a few locations, follow-up surveys have been hampered by outwash cover. If the glacial geology is favourable, it is our experience that the source of the anomalous glacial dispersion train can be located within a few hundred metres or less.

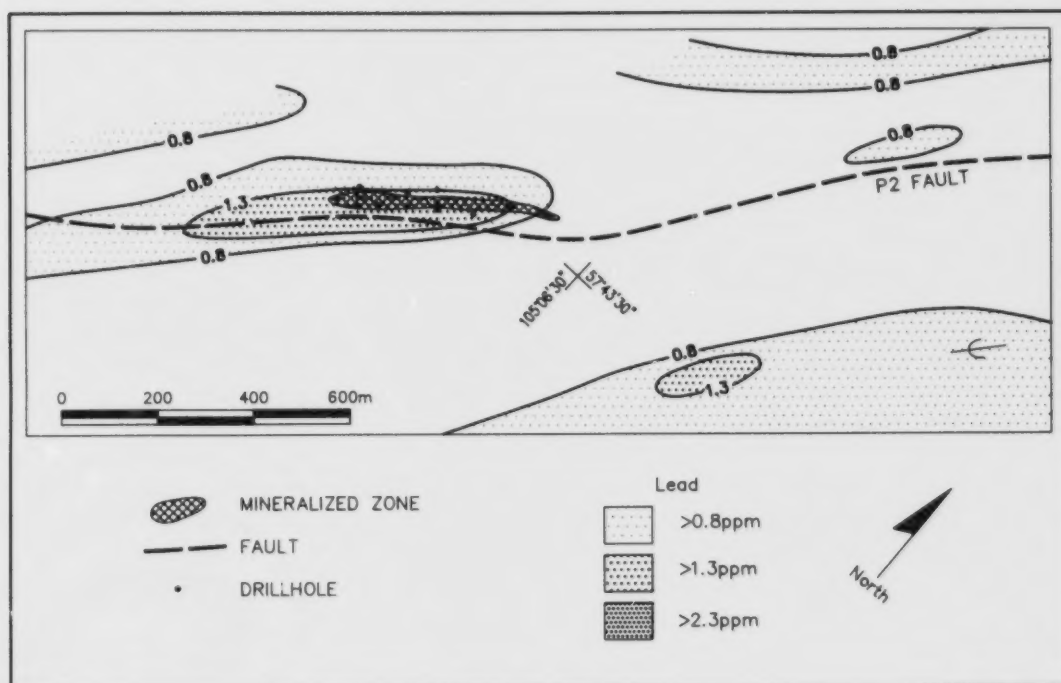


Figure 24 - Distribution of lead in boulders on the McArthur River property.

Other Applications

Composite glacial boulder sampling should be a viable exploration method in other mineral provinces providing that there are; 1) a suitable glacial history, 2) predictably low element background in the cover rocks, and 3) recognizable geochemical halos above the mineral deposits. Other paleo-Helikian basins in Canada such as the Hornby and Baker Lake areas would meet these criteria. This method would be particularly effective on targets that have no obvious geophysical signature.

CONCLUSIONS

Within the Athabasca Basin of northern Saskatchewan, boulder lithogeochemistry has proven to be an efficient and effective tool in the search for buried uranium deposits. The technique provides rapid and inexpensive exploration coverage of large project areas. For example, a property of 200 km² can be covered for the cost of one deep drill hole. If significant uranium mineralization is present, it is highly probable that its alteration halo will be evident in boulder trains and that a target for drill testing will be defined after more detailed boulder sampling.

Although a boulder survey stands on its own, the surficial lithogeochemical distribution which it provides can best be interpreted in conjunction with other exploration data, particularly those provided by mag-

netic and electromagnetic surveys. A knowledge of the nature of alteration patterns to be expected in the study area is also essential in order to properly interpret the results of a boulder survey.

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ACKNOWLEDGEMENTS

The authors thank the owners of the five projects surveyed, as listed below, for permission to release data of samples collected on their properties and information on methods developed during the course of exploration on these properties:

Cree Extension Project:

Cameco - A Canadian Mining & Energy Corporation
CEGB Exploration (Canada) Ltd.
Interuranium Canada Ltd.
PNC Exploration (Canada) Co. Ltd.
Union Carbide Canada Ltd.
Uranerz Exploration and Mining Limited (Operator)

Epp Lake Project:

CEGB Exploration (Canada) Ltd.
Uranerz Exploration and Mining Limited (Operator)

Hughes Lake Project:

AGIP Canada Ltd.
Anglo-Bomarc Mines Ltd.
Cameco - A Canadian Mining & Energy Corporation
Chevron Minerals Ltd.
Thor Explorations Ltd.
Uranerz Exploration and Mining Limited (Operator)

McArthur River Project:

AGIP Canada Ltd.
Cameco - A Canadian Mining & Energy Corporation (Operator)
Cogema Canada Limited
E & B Exploration Ltd.
Interuranium Canada Ltd.
Uranerz Exploration and Mining Limited

Read Lake Project:

Cameco - A Canadian Mining & Energy Corporation
Chevron Minerals Ltd.
Kerr Addison Mines Limited
Uranerz Exploration and Mining Limited (Operator)

In addition, the authors thank all the members of the Uranerz and Cameco exploration teams for their contributions to this work.

THE USE OF STABLE AND RADIOGENIC ISOTOPES IN THE IDENTIFICATION OF FLUIDS AND PROCESSES ASSOCIATED WITH UNCONFORMITY-TYPE URANIUM DEPOSITS

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ABSTRACT

The Athabasca Basin in northern Saskatchewan has had a complex fluid history since its formation in mid-Proterozoic times. Fluid flow within the basin is responsible for the development of a number of high-grade, unconformity-type uranium deposits that have developed at the contact between Aphebian gneisses and pelites and the overlying Helikian Athabasca sandstones. Stable isotope systematics of clays and other minerals associated with the alteration haloes surrounding the deposits reveal a hydrothermal mixing zone consisting of isotopically distinct basement and basin fluids at the intersection between deep-rooted basement faults and the overlying sandstones. Sulphur isotopic compositions of Ni-As-S and sulphide minerals near the Key Lake orebody, and within alteration haloes of other deposits, also indicate the existence of a mixing zone between isotopically and chemically distinct basement and basin fluids. Carbon isotopic compositions of hydrocarbon buttons and graphitic gneisses near the deposits indicate that the destruction of graphite did not result in the formation of CH₄ as reductant for the uranium. Rather, the graphite has assumed a more passive role by providing suitable areas for faulting in which the mineralizing fluids could be channeled. Since formation of the high grade uranium deposits from the mixing of basement and basin fluids at 200°C, permeable shear zones within the basin have been affected by late-stage incursions of fluids which have (1) remobilized uranium into later fractures, (2) formed kaolinite with stable isotopic signatures that are distinct from the minerals which formed from the hydrothermal fluids, and (3) affected both the chemical and isotopic compositions of earlier formed chlorite and illite occurring within the ore zones. Identification of these changes allows the structures which may host the uranium ore deposits to be identified and permits an assessment of the intensity of the ore-forming hydrothermal and later alteration events within the basin. Rb-Sr ages of illite associated with the hydrothermal basin fluid are 1477 ± 57 Ma whereas K-Ar ages vary from 1350 to 750 Ma indicating the susceptibility of K-Ar systematics to resetting by later events. Rb-Sr ages of 1477 Ma for illites and U-Pb ages of 1406 Ma for uraninite at Key Lake indicate the onset of hydrothermal alteration and associated uranium mineralization early in the history of the basin.

INTRODUCTION

The movement of fluids over large distances in sedimentary basins is involved in many geologic processes, notably the transportation and deposition of metals in sediment-hosted ore deposits. Mineralogical and geochemical evidence can be used to document the existence of these large-scale fluid movements through sedimentary basins since any fluid that migrates through porous rocks may leave evidence of water/rock reactions. Mineralogical zonation around hydrothermal systems may be obvious for tens to a few hundred metres, however, large

scale fluid flow events that are basinwide and more pervasive may be very subtle and harder to discern. In the Athabasca Basin, the sedimentary rocks have been affected by a number of different fluids which have left their mark in the geochemical, mineralogical, and isotopic compositions of clay minerals, fluid inclusions, and uranium-bearing minerals throughout the basin.

Following the discovery of the Proterozoic unconformity-type uranium deposits in the Athabasca Basin, northern Saskatchewan has become an important

uranium producing area. Initial discoveries at Rabbit Lake and Cluff Lake and subsequent discoveries at Key Lake, Midwest Lake and, most recently, Cigar Lake (Figure 1) have revealed marked similarities in most unconformity-type uranium deposits and contributed greatly to the geological data base for the evolution of the Athabasca Basin. Synchronous dis-

coveries of unconformity-type uranium deposits in the Northern Territory of Australia, which are similar in age, sedimentary and structural settings, geochemistry and host-rock alteration, indicate similar processes for the formation of these uranium ores (Kirchner *et al.*, 1980; Maas, 1989).

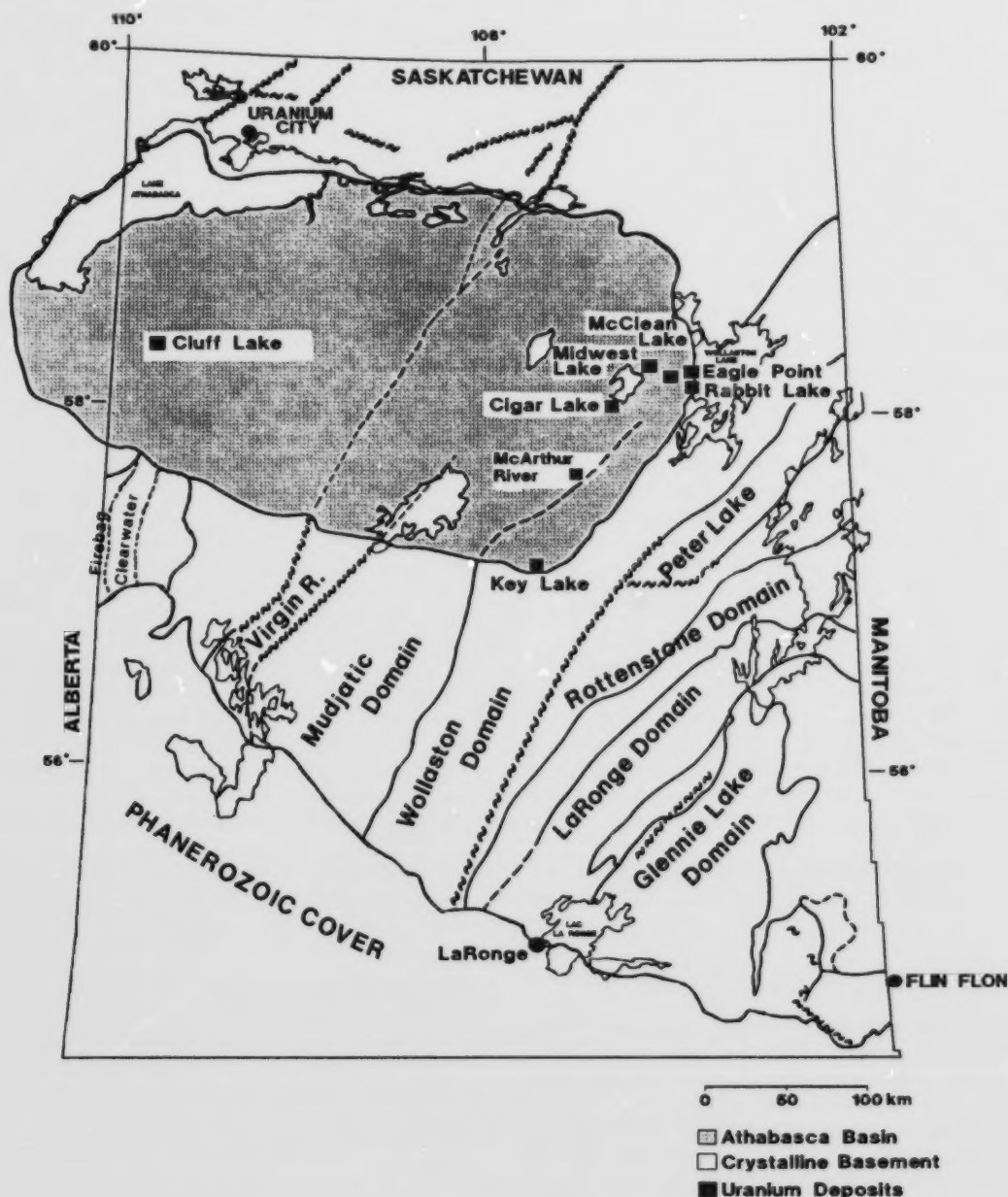


Figure 1 - Map showing the extent of the Athabasca Basin, locations of uranium deposits and major lithostructural domains in the crystalline basement of Saskatchewan (after Hoeve and Sibbald, 1978).

Despite their economic significance, there is little consensus as to the genesis of the deposits. Initial theories proposed were based on an erosional model due to the proximity of the ore to the unconformity (Langford, 1974; Knipping, 1974). Later models suggested large-scale fluid movement and diagenesis within the Athabasca Sandstones (Hoeve and Sibbald, 1978; Hoeve *et al.*, 1980). Recently, a modification of the diagenetic - hydrothermal model suggests that uranium transport and deposition is linked with the fluid-flow hydrodynamics, time-temperature profiles and geochemical conditions that existed within the Athabasca Basin (Hoeve and Quirt, 1984; Wilson and Kyser, 1987; Kyser *et al.*, 1988). This model not only involves the need for large-scale fluid movements to transport the uranium, but also recognizes the importance of structural features and fluid mixing in the deposition of the uranium (Wilson and Kyser, 1987; Hoeve and Sibbald, 1978; Wallis *et al.*, 1982). The development of a unified fluid-flow model within the Athabasca Basin is of economic interest because similar mechanisms of epigenetic ore deposition by large-scale fluid movements are proposed for the formation of stratiform copper, lead-zinc and hydrothermal platinum deposits. The similar processes involved in the formation of all these deposits suggest that the Athabasca Basin may contain more than uranium in economic concentrations (Brown, 1971; Gustafson and Williams, 1981).

In order to adequately assess the mechanisms involved in the formation and preservation of unconformity-type uranium deposits, an overall picture of the fluid flow systematics within the basin must be developed. As water is the dominant component in the fluids involved, the stable isotopic composition of oxygen and hydrogen within fluid inclusions and silicate minerals associated with various stages of the basin development can be used to delineate the various fluids involved. Microthermometric and stable isotope analysis of fluid inclusions, which occur in some of the silicate minerals associated with the hydrothermal alteration, can be measured to constrain the temperature, chemistry, and isotopic composition of the fluids. In addition, sulphide minerals of varying paragenesis, as well as graphite and carbonaceous material occurring in the alteration haloes and elsewhere in the basin, can be used to constrain the sources of the fluids and yield information on the structural development of the basin. Rb-Sr and K-Ar systematics have been used to determine the ages of the minerals, sources of the fluids and ages of subsequent alteration events in the vicinity of the alteration haloes around the uranium deposits.

REGIONAL GEOLOGY AND ALTERATION

The Athabasca Basin, formed at approximately 1700 Ma (Armstrong and Ramaekers, 1985), consists of a thick sequence of mature quartz sandstones, shales and carbonates overlying a series of Archean gneisses and Aphebian metasediments which are separated by a well-developed unconformity and paleosol (Tremblay, 1982). The paleosol beneath the unconformity generally extends for several metres depth, within which the basement gneisses are strongly altered to illite, kaolinite and chlorite. Proterozoic uranium deposits occur at or near the intersection of fault zones rooted in the basement metasedimentary rocks and the unconformity. Intense hydrothermal alteration in the sandstones and basement gneisses surrounding the uranium deposits consists of illite, tourmaline, euhedral quartz and chlorite assemblages (Hoeve *et al.*, 1980; Wallis *et al.*, 1982). Adjacent to the deposits, the dominantly illitic sandstones show evidence of quartz dissolution (Hoeve *et al.*, 1981). In the Manitou Falls Formation, the sandstone-clay sequences have been extensively hematized, particularly along thin, stratigraphic horizons, indicating oxidation of pre-diagenetic heavy mineral suites. The occurrence of superimposed uranium and kaolinite assemblages, Fe-chlorites and chemically altered illites in the fault zones that host high-grade uranium attests to a period of later, low-temperature alteration by meteoric waters.

Associated with the fault structures at most of the unconformity-type uranium deposits are graphite-rich gneisses and pelites, which are thought to have provided a structural, rather than a chemical control, on the deposition of the uranium (Kyser *et al.*, 1988). Within the hydrothermal alteration halo surrounding the deposits is a variable suite of sulphur-bearing minerals that range from a Ni-Co-As-S association with galena and late pyrite/marcasite at Key Lake (Ruhmann and Von Pechmann, 1989); minor amounts of pyrite, chalcopyrite and galena at Eagle Point (Eldorado Resources, 1986); and chalcopyrite, pyrite and small amounts of sphalerite and galena at McArthur River.

STABLE AND RADIOGENIC ISOTOPE SYSTEMATICS: THEORETICAL CONSIDERATIONS

Hydrogen and Oxygen Isotopes

Large-scale fluid movements and fluid mixing resulted in the transport and deposition of uranium, and development of alteration haloes around the deposits, as well as diagenetic alteration of primary mineral assemblages in the sediments far-removed from uranium mineralization (Hoeve and Sibbald,

1978; Hoeve and Quirt, 1984; Pagel *et al.*, 1980; Wilson and Kyser, 1987). Subsequently meteoric fluids, which gained access to the deeper levels of the Athabasca Basin along reactivated faults, altered the uranium and co-existing mineral assemblages.

Because water is the dominant constituent of an ore-forming fluid, characterization of the water will help refine the ore deposit model. The fluid's character can be determined by measuring either the hydrogen and oxygen isotopic compositions of the water directly using fluid inclusions, or their values in hydrous mineral assemblages for which the temperatures of formation have been determined. Using experimentally and empirically derived mineral-water isotopic fractionation factors, the isotopic composition of the fluids from which the minerals have formed can then be calculated (Taylor, 1974).

The mass of a water molecule depends on the isotopic composition of its constituent elements, namely oxygen and hydrogen. Therefore, the mass of the water will depend on the amount of deuterium relative to hydrogen and ^{18}O relative to ^{16}O , or the D/H and $^{18}\text{O}/^{16}\text{O}$ ratios. In order to compare these isotopic ratios, they are measured relative to Standard Mean Ocean Water (SMOW), and reported as relative differences from SMOW in units of per mil (1 per mil = 0.1%). The isotopic composition of water relative to SMOW can be expressed as the delta value (δ):

$$\delta = \left(\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1 \right) \times 1000$$

where R_{sample} and R_{standard} are the D/H or $^{18}\text{O}/^{16}\text{O}$ in the sample and standard, respectively (Taylor, 1974).

Since the isotopes of H- and ^{16}O -rich water molecules vibrate faster and have a higher potential energy than D- and ^{18}O -rich water for a given temperature, H and ^{16}O tend to be concentrated in the vapor phase. If meteoric water vapor is repeatedly condensed in steps, it undergoes Rayleigh distillation and the remaining vapor will become progressively more depleted in D and ^{18}O . One result of this is that meteoric waters, which move over large continental land masses and continually lose water via precipitation, become depleted in the heavier isotopes of oxygen and hydrogen (Sheppard, 1986). Therefore, meteoric waters in Saskatchewan have δD and $\delta^{18}\text{O}$ values of -140 and -20 per mil, respectively, whereas meteoric water in Vancouver has δD and $\delta^{18}\text{O}$ values of -90 and -10 per mil, respectively, relative to SMOW (*ibid*). In addition, storms that form from evaporation of seawater at high latitudes and move inland have lower δD and $\delta^{18}\text{O}$ values than

those that originate at low latitudes because air is cooler at higher latitudes and the fractionation of isotopes between liquid and vapor is larger at these cooler temperatures. This latitudinal effect produces meteoric waters of various and distinct stable isotopic compositions and makes the Athabasca Basin particularly amenable to tracing fluid events with stable isotopes. Since formation at approximately 1700 Ma in a low-latitude coastal environment where the waters would have had relatively high δD and $\delta^{18}\text{O}$ values (Armstrong and Ramaekers, 1985; Wilson and Kyser, 1987), the Athabasca Basin has generally been moving progressively northwards to its current position in a relatively high-latitude, low-temperature environment (Fahrig *et al.*, 1978) where the meteoric waters are substantially more depleted in D and ^{18}O . Clay minerals, which are ubiquitous in the sedimentary rocks of the Athabasca Basin, the hydrothermal halos around the uranium deposits, and in the late-formed alteration assemblages along re-activated faults, are ideal candidates for isotopic studies because they formed from or have been altered by various fluids through time and therefore may be used to develop the fluid history of the basin.

The isotopic composition of fluids in most sedimentary basins is due to a mixture of modern meteoric water and ancient formation waters (Clayton *et al.*, 1966), the latter being ^{18}O -rich because of reactions between the formation waters and sediments over long periods of time (i.e. millions of years). Mixing of these two components in various proportions results in waters from a given sedimentary basin having a considerable range of isotopic compositions (Gulf Coast and Alberta Basin waters - Figure 2) that vary between modern meteoric water and an evolved basinal brine. In basins with connected aquifers having high hydraulic conductivities, such as the Athabasca Basin during deposition, the isotopic compositions of the waters in the basin tend to be similar, especially in deeper portions of the basin.

The primary control on the fractionation of hydrogen and oxygen isotopes between clay minerals and water is the temperature and crystal structure of the clay mineral (Kyser, 1987). Since the major clay mineral groups are classified on the basis of various combinations of tetrahedral and octahedral layers and associated cations, they have different stable isotope fractionations with water as a function of temperature. The hydrogen and oxygen isotopic fractionation factors with temperature have been experimentally and empirically derived for different clay minerals (*ibid*). If the temperature at which the clay mineral formed can be determined, the δD and $\delta^{18}\text{O}$ values of the clay minerals can be combined with the appropriate fractionation factor for the clay mineral to determine the isotopic composition of the fluid. In

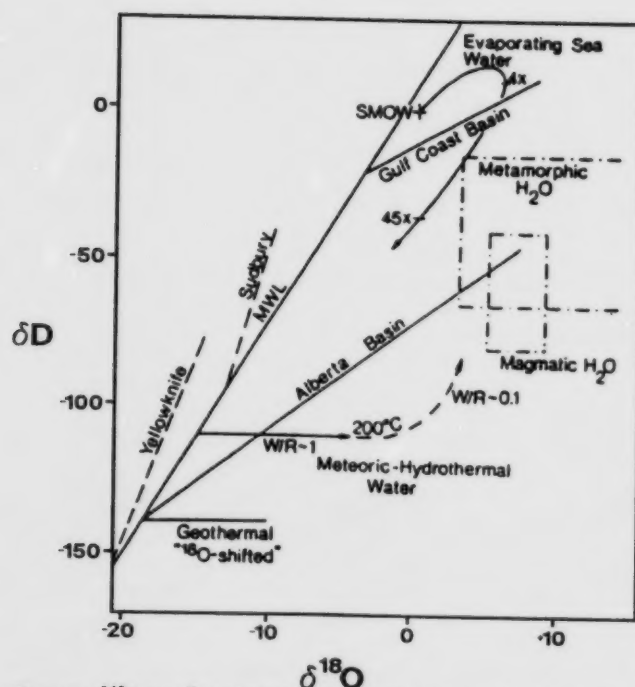


Figure 2 - $\delta^{18}\text{O}$ and δD values for typical fluids associated with various geologic processes. Fluids within sedimentary basins have values that vary between modern meteoric water, indicated by the meteoric water line (MWL) along which most meteoric waters plot, and highly evolved basinal fluids (Alberta Basin and Gulf Coast Basin fluids). Also shown are the $\delta^{18}\text{O}$ and δD values of minerals from the Canadian Shield (Yellowknife and Sudbury lines) and metamorphic and magmatic waters. Horizontal line for meteoric-hydrothermal waters shows the direction the isotopic composition of the water moves in response to interaction with rocks.

the Athabasca Basin, the temperatures of formation for the various clay minerals determined by fluid inclusion temperatures in associated quartz and carbonate (Pagel *et al.*, 1980), stable isotopic geothermometry between co-existing minerals (Wilson and Kyser, 1987), and the crystallinity index of the clay minerals (Dunoyer De Segonzac, 1970; Hoeve *et al.*, 1981) indicate that maximum diagenesis and formation of the uranium deposits occurred at 200°C and that later fluids at approximately 50°C affected some of the clay minerals.

Carbon Isotopes

The abundance of graphite in the basement gneisses and pelites underlying the Athabasca Basin and the spatial association of graphite to the uranium deposits has led to proposals that the graphite was consumed by a reaction with hydrothermal fluids to form methane, which then acted as a reductant for the uranium (Hoeve and Quirt, 1984; Hoeve and Sibbald, 1978; Dubessy *et al.*, 1988). In addition, the occurrence of hydrocarbon buttons and bituminous material in the vicinity of the alteration haloes as-

sociated with the uranium deposits has been attributed to the condensation of methane produced by graphite alteration (Hoeve and Quirt, 1984; Landais *et al.*, 1987).

Graphite undergoing alteration to methane should result in residual graphite that is significantly enriched in the heavy isotope of carbon (^{13}C) whereas the methane is enriched in the light carbon isotope (^{12}C) (Ohmoto, 1986; Kyser *et al.*, 1988). Ohmoto (1986) also suggests that when graphite is oxidized to form CO_2 , there is little or no significant fractionation of the carbon isotopes. Therefore the $\delta^{13}\text{C}$ values of carbon in altered and unaltered graphites and bituminous materials should be indicative of whether or not the conversion of graphite to methane and the reduction of uranium by this methane was instrumental in the formation of the unconformity-type uranium deposits.

Sulphur Isotopes

Sulphur in many hydrothermal ore deposits is fixed as either sulphides or sulphates and is thought to have originated either from a seawater or igneous source. The stable isotopic composition of sulphur in sulphides is controlled by a number of factors including: the oxygen fugacity of the system, the presence of sulphate-reducing bacteria, whether closed or open system conditions prevailed during the formation of the sulphur-bearing minerals, and the temperatures at which the sulphide minerals formed. The fractionations of sulphur isotopes between oxidized and reduced forms of sulphur are substantial (i.e. several per mil) so that sulphur-bearing minerals forming in redox conditions will have variable $\delta^{34}\text{S}$ values. In order to use the $^{34}\text{S}/^{32}\text{S}$ ratios of sulphides and sulphates as isotopic tracers, the system in which they formed must behave as a closed system with the sulphur existing as either a reduced or an oxidized species (Kyser, 1987). If a large number of co-existing sulphides have a constant $\delta^{34}\text{S}$ value, the oxidation state of sulphur must have been below a certain $\text{SO}_4/\text{H}_2\text{S}$ ratio in a closed system or remained constant in an open system (Ohmoto, 1986). If a significant amount of oxidized sulphur is present as sulphides are forming in a closed system, the sulphide minerals will become increasingly enriched in ^{34}S as the sulphur is removed from the oxidized reservoir.

Rubidium-Strontium and Potassium-Argon Isotopes

The rubidium and strontium isotopic composition of minerals can be used to constrain the timing and the

sources of fluids (Faure, 1986). In sedimentary sequences, however, the application of Rb-Sr systematics to ascertain the timing of geologic events may be tenuous since minerals, especially in sedimentary environments, are prone to later alteration. Alteration of minerals in sedimentary environments tends to decrease their $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and increase their Rb/Sr ratios leading to erroneously younger ages. Meaningful ages may be obtained if sediments undergo a period of early diagenesis during which rubidium and strontium are sufficiently homogenized. A stable Rb-Sr system may result if it is not affected by any later alteration events (Clauer, 1979).

K-Ar systematics have been applied extensively to determining the age of minerals. Fine-grained minerals, particularly clay minerals, have been proven to be inherently non-retentive of argon during periods of metamorphism, hydrothermal activity, and later weathering (Clauer, 1979). Therefore, K-Ar ages of clay minerals in areas that have had an extensive and complicated geologic history may be indicative of subsequent events rather than ages of formation (Clauer, 1981; Faure, 1986).

RESULTS AND DISCUSSION

Stable and radiogenic isotopic analyses and fluid inclusion microthermometry have been determined for the mineral assemblages within the alteration haloes associated with the unconformity-type uranium deposits, and the diagenetically altered sandstones in the Athabasca Basin. These studies show that the Athabasca Basin has been affected by a minimum of three isotopically and chemically distinct fluids: a basement-derived fluid, a basinal brine and a late, meteoric water.

Basement Fluid

Mg-chlorites, which occur in the altered regolith and gneisses around the Key Lake uranium deposit (Wilson and Kyser, 1987), and are spatially associated with the fracture-controlled mineralization at the Eagle Point uranium deposit are believed to have been in equilibrium with high temperature (approx. 200°C), reducing fluid. δD and $\delta^{18}\text{O}$ isotopic values of the chlorites from Key Lake indicate they formed in equilibrium with a fluid that has a similar isotopic composition to a Gulf-Coast basinal fluid at 200°C (Figure 3) (*ibid*). Wilson and Kyser (1987) postulated that the Mg-chlorite, which is restricted mainly to the altered basement gneisses, formed as a result of interaction between a reducing basement fluid emanating along the fault zones, which host the deposit and the surrounding gneisses.

Basinal Brine

A high-temperature (approx. 200°C), oxidizing basinal fluid has been identified in equilibrium with highly-crystalline illite intergrown with the Mg-chlorite at Key Lake (Wilson and Kyser, 1987); uranium mineralization at Eagle Point, McArthur River and Midwest Lake; and regional diagenetic clay within the sediments of the Manitou Falls Formation (Hoeve and Quirt, 1984). These fluids are similar in isotopic composition to a mid-latitude basinal brine, such as in the Alberta Basin (Figure 3). Euhedral quartz occurring in the illite-rich hydrothermal haloes surrounding many of the uranium deposits (Hoeve *et al.*, 1981) has oxygen isotopic values which yield a fluid with a calculated $\delta^{18}\text{O}$ value similar to the oxygen isotopic composition of the high-temperature basinal brine from which the illite formed. The hydrogen isotopic composition of the fluids from fluid inclusions in the euhedral quartz yields a δD value (-53 per mil; Figure 3) that is similar to the hydrogen isotopic composition of the hydrothermal fluid calculated to be in equilibrium with the illite. Thus, the isotopic similarity of the fluids in equilibrium with the illite and euhedral quartz suggests that they formed from the same fluid event.

Euhedral quartz from McArthur River and Eagle Point contain three-phase fluid inclusions (liquid + vapor + halite cube) which yield homogenization temperatures ranging from 180 to 230°C and salinities of 30-34 wt. % NaCl equivalents. The temperatures and high salinities of these fluids are comparable to measurements obtained from quartz and carbonate elsewhere in the basin (Pagel *et al.*, 1980) and are similar to temperatures obtained from oxygen isotope geothermometry between co-existing quartz and illite at Key Lake (Wilson and Kyser, 1987). The regional similarity of temperatures associated with this event indicates a high permeability in the Manitou Falls sediments and the development of large-scale basinal fluid flow.

Dravite tourmaline, which occurs in the alteration haloes of many unconformity-type uranium deposits in the Athabasca Basin (Hoeve and Sibbald, 1978; Ruhrman, 1986; Wilson and Kyser, 1987; Pagel *et al.*, 1980), is similar to the diagenetic tourmalines in the Pine Creek Geosyncline (Bone, 1988) and in the Belt-Purcell Supergroup (Beatty *et al.*, 1988). An early stage of dravite, associated with euhedral quartz in quartz-tourmaline breccia zones and as dravite needles along growth planes in the euhedral quartz, appears to have formed in equilibrium with the quartz. The $\delta^{18}\text{O}$ values of this dravite are similar to the $\delta^{18}\text{O}$ values of the illite in the alteration haloes, and it appears that the dravite formed in equilibrium with the same high-temperature, oxidizing basinal brine

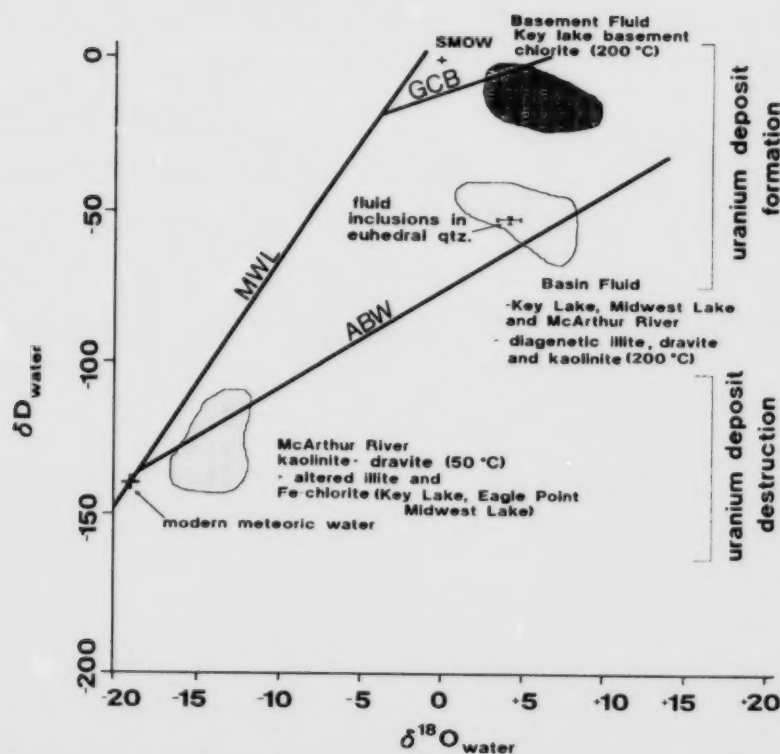


Figure 3 - Calculated $\delta^{18}\text{O}$ and δD values for various fluids associated with unconformity-type uranium deposits in the Athabasca Basin. Shaded areas represent fluids calculated to be in equilibrium with 1) basement chlorite at 200°C from Key Lake (Wilson and Kyser, 1987) (Basement Fluid), 2) diagenetic illite at 200°C from Key Lake (ibid), Midwest Lake (ibid), McArthur River and Eagle Point (Basin Fluid), and 3) kaolinite and dravite associated with remobilized uranium in fractures at McArthur River and responsible for retrograde alteration of illite and chlorite at Key Lake, Midwest Lake and Eagle Point. Also shown are values for modern meteoric waters in the Athabasca Basin and the isotopic composition of fluids within fluid inclusions in euhedral quartz. Meteoric water line is indicated by MWL, waters in a Gulf Coast Basin by GCB, and waters in the Alberta Basin by ABW.

responsible for the formation of the diagenetic illite. The dravite associated with the uranium deposits may have formed in a similar fashion to Mg-rich tourmalines at the Kidd Creek (Slack and Coad, 1988) and Sullivan massive sulphide deposits where it is believed that excess Mg existed in the hydrothermal system. In the Athabasca Basin, boron was most likely liberated from the clays during diagenesis, as has been suggested for tourmalines occurring in other sedimentary-hydrothermal systems (Taylor and Slack, 1985; Lydon, 1983). Magnesium was most likely derived from the basement rocks during alteration of Fe-Mg silicates to Mg-chlorite. Excess magnesium was transported by the reducing basement fluid and boron by the oxidizing basinal fluids to the areas where fluid mixing took place and resulted in dravite being formed in the alteration haloes associated with uranium deposition. Further evidence that dravite is linked to the hydrothermal and uranium deposition is

seen at the Jabiluka uranium deposit in Australia where dravite occurs as inclusions and along cleavage planes in coarse-grained Mg-chlorites which formed from alteration of the Fe-Mg silicates in metasediments hosting the uranium mineralization (Nutt, 1989). Neodymium and strontium isotopic analysis of the chloritic alteration at Jabiluka indicates that the associated uranium precipitated from fluids that reacted with both the basement rocks and the overlying Kombolgie sandstones (Maas, 1989). This is also suggested by oxygen isotopic analysis of alteration assemblages at Jabiluka uranium deposit (Ypma and Fuzikawa, 1981), supporting the idea of multiple fluids responsible for uranium deposition at Jabiluka, much the same as in the Athabasca Basin.

Late Meteoric Water

A late-stage, low-temperature ($< 50^\circ\text{C}$) fluid with δD and $\delta^{18}\text{O}$ values similar to modern-day meteoric waters (Figure 3) is recorded by stable isotopic compositions of kaolinite associated with remobilized uranium and late dravite in re-activated fault zones in the McArthur River area. This late meteoric water event has also chemically and isotopically altered illite and Mg-chlorite in fault zones within the high-grade uranium ore at Key Lake and Midwest Lake (Wilson *et al.*, 1987), and illite occurring with uranium mineralization in the fractures at Eagle Point. In addition to having hydrogen isotopic compositions approaching that of meteoric water, the illites have also undergone chemical alteration indicated by lower K_2O content, an increased water content, and by resetting of K-Ar systematics to give variably younger ages. As retrograde alteration of the illites proceeded, their δD values became progressively lower, H_2O replaced K_2O in the illite structure, and radiogenic argon was displaced resulting in variable and younger K-Ar ages. The process of retrograde alteration of illite and chlorite, and forma-

tion of late kaolinite and dravite within the uranium deposits is due to the large-scale incursion of meteoric waters along the re-activated fault zones which host these deposits. In areas where the quantity of meteoric water involved is substantial, the uranium has been remobilized significantly and the sediments have undergone widespread kaolinitization. This late meteoric water event, which has a distinctive geochemical and isotopic signature, is ultimately responsible for the varying degrees of preservation of the uranium deposits in the Athabasca Basin.

Chemical and isotopic alteration of the illites has occurred irrespective of the amount of uranium associated with the clay minerals. This is in contrast to the mechanism implied by Halter *et al.* (1987), who reported a direct correlation between the δD value and uranium content of the clay minerals associated with uranium mineralization at the Cluff Lake uranium deposit. They suggest that clays containing higher concentrations of uranium have increasingly lower δD values due to the effects of radiation damage. They believe that the correlation between decreasing δD values and increasing uranium values may be envisioned as a possible exploration guide for uranium mineralization. However, when the data from a number of Athabasca Basin uranium deposits is compared (Figure 4), no obvious correlation exists between uranium content and δD values of the clay minerals. Rather, a correlation exists between the isotopic and chemical alteration of the clay minerals and the development of enhanced permeability due to fault re-activation in areas of uranium mineralization which is indicative of retrograde alteration of the clay minerals by meteoric waters. Such phenomena are not solely restricted to the clay minerals in the Athabasca uranium deposits, but have been recognized in other geologic environments, devoid of uranium, such as serpentine in asbestos deposits (O'Hanley *et al.*, 1989) and kaolinite in laterites (Bird and Chivas, 1988) where interaction with later meteoric waters has occurred.

The fluids, responsible for a) diagenesis of the Athabasca sediments, b) formation of the hydrothermal alteration halo surrounding the uranium deposits, and c) later retrograde alteration, have a range of hydrogen isotopic compositions (Figure 5).

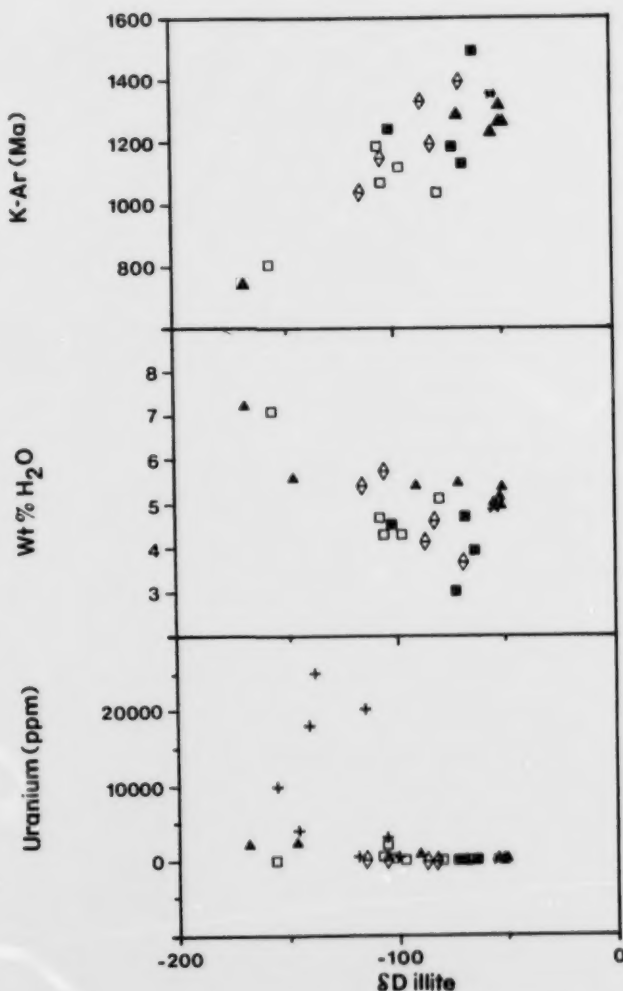


Figure 4 - Relation between δD , wt.% water, K-Ar ages and uranium contents of illites from Rumble Lake (*), Midwest Lake ($\square$), Key Lake ($\blacksquare$) (Wilson *et al.*, 1987), McArthur River ($\diamond$), Cluff Lake ($\blacktriangle$) (Halter *et al.*, 1987) and McClean uranium deposit (Bray *et al.*, 1988). Lack of correlation between the δD values and uranium contents in the illites indicates that the chemical and isotopic alteration of the clay minerals is not due to radiation-induced effects (Halter *et al.*, 1987). The occurrence of chemically and isotopically altered illite and chlorite in the permeable fault zones associated with uranium mineralization (Wilson and Kyser, 1987) indicates clay mineral alteration by meteoric waters.

The δD values of fluids in equilibrium with illite and Mg-chlorite at Key Lake indicate two isotopically distinct fluids, a basement fluid and basinal brine. Subsequent low-temperature alteration of the uranium deposits along highly permeable fault zones caused remobilization of the uranium, retrograde alteration of associated chlorite and illite and produced low-temperature kaolinite and dravite with δD values suggestive of the presence of meteoric waters. Since this late alteration event is permeability controlled, the

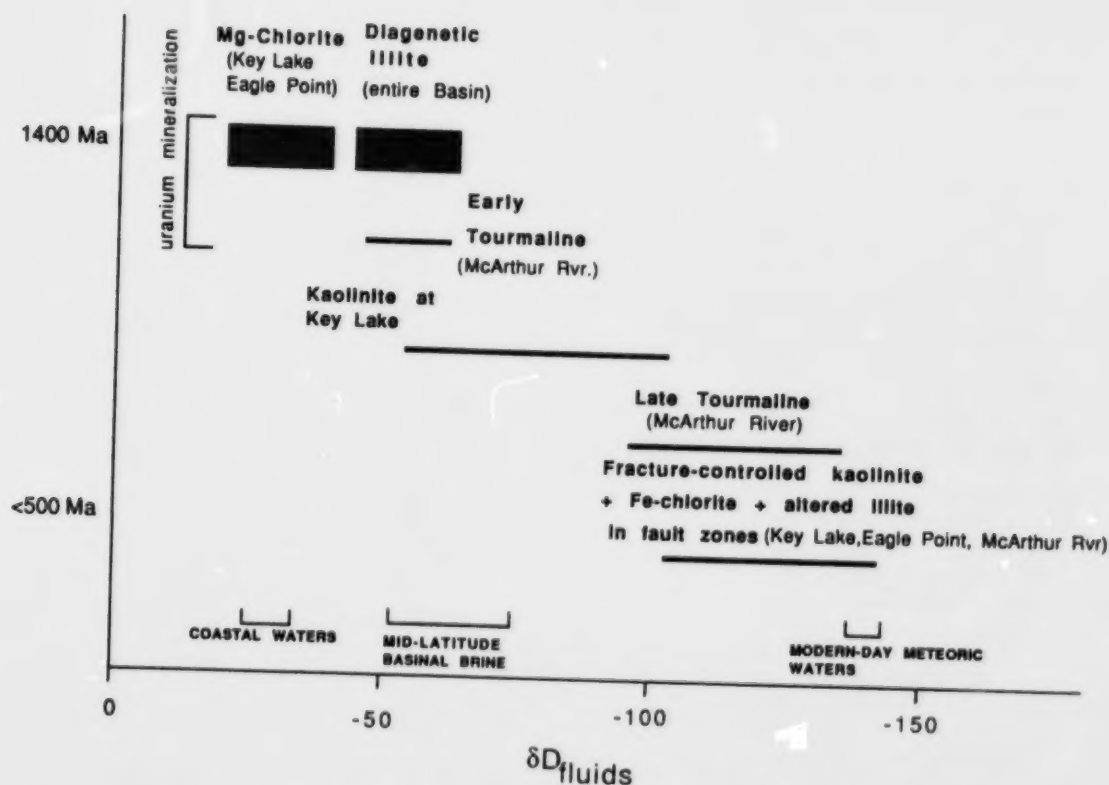


Figure 5 - Range in the δD values of the fluids versus relative ages for minerals within the Athabasca Basin. Uranium mineralization at approximately 1400 Ma is due to fluid mixing between an isotopically distinct basement and basin fluid at 200°C which is recorded in the isotopic compositions of chlorite and illite (shaded areas) and dravite. As time progresses, minerals have increasingly lower δD values indicative of the incursion of meteoric water into the basin. Also shown are the δD values for 1) coastal waters (basement fluid), 2) mid-latitude basinal waters (basin fluid) and 3) modern day meteoric waters in the Athabasca Basin.

degree of isotopic and chemical alteration of the sandstones and destruction of the high-grade uranium deposits is directly dependant upon the magnitude of the later fracturing events that re-activated fault zones in and around the uranium deposits.

Sulphur isotopic compositions of sulphides further constrain the fluid compositions during development of uranium deposits in the Athabasca Basin. The range of $\delta^{34}S$ values for both millerite and gersdorffite from the Ni-Co-As pods associated with uranium mineralization at Key Lake and chalcopyrite associated with uranium at McArthur River suggest fluid mixing between two isotopically distinct fluids (Figure 6). The two end-member fluids consist of a basement fluid with $\delta^{34}S$ values near 0 per mil and a basin fluid containing a component of Proterozoic seawater having a $\delta^{34}S$ value near +12 per mil (Kotzer *et al.*, in prep.). The narrow ranges of $\delta^{34}S$ values for millerite, gersdorffite and chalcopyrite as-

sociated with uranium mineralization reflects the reducing nature of the hydrothermal system in the vicinity of the uranium deposits.

Pyrite occurring in late fractures in the alteration haloes and elsewhere in the basin has highly variable $\delta^{34}S$ values (Figure 6). This variation is attributed to leaching of sulphur from pre-existing sulphides by oxidizing fluids and the incorporation of sulphur in areas of variable oxygen fugacity due to incursion of late, oxidizing meteoric waters. Lead sulphate minerals occurring in the lead dispersion haloes in the sandstones above the Key Lake uranium deposits have Devonian Pb-Pb ages and $\delta^{34}S$ values similar to Devonian seawater sulphate (Kotzer *et al.*, in prep.) indicating the occurrence of late-stage fluid movement in and around the uranium deposits. The late paragenesis of pyrite in fractures coupled with highly variable $\delta^{34}S$ values indicates their formation during periods of extreme fO_2 variations believed to have

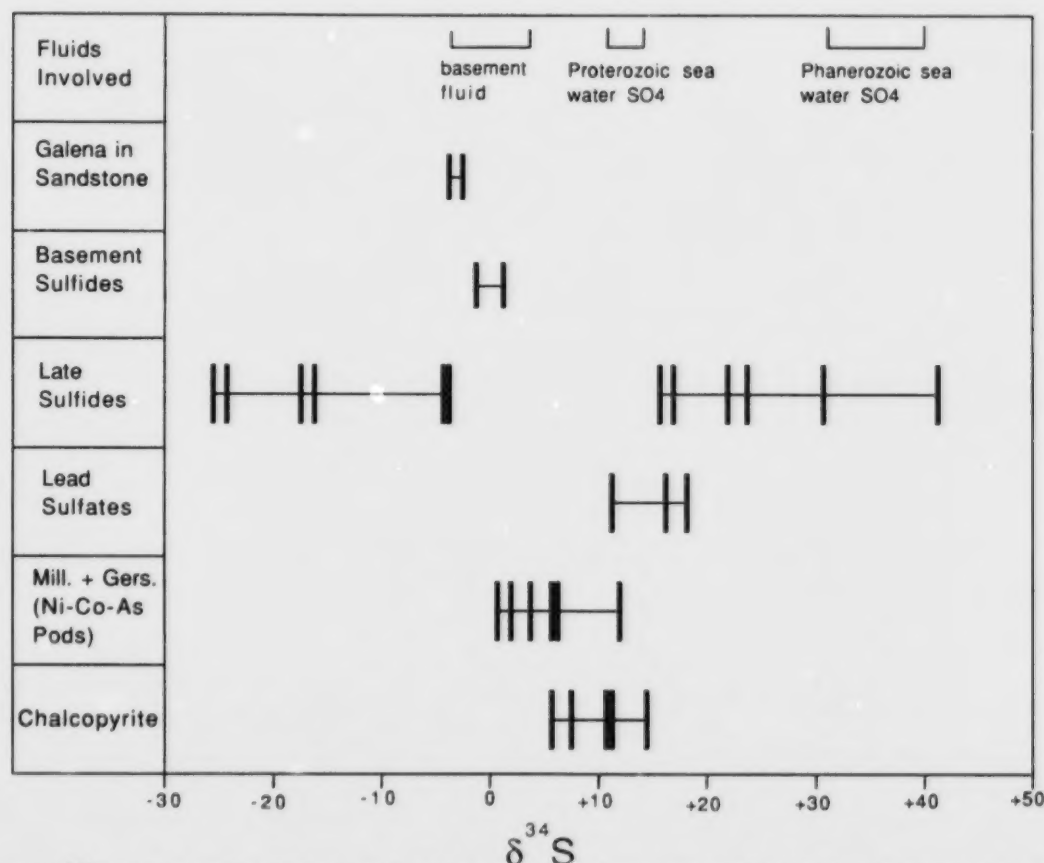


Figure 6 - $\delta^{34}\text{S}$ values of various sulphides and sulphates occurring within and outside of the hydrothermal alteration haloes in the Athabasca Basin. Millerite and gersdorffite from Ni-Co-As pods at Key Lake and chalcopyrite at McArthur River, which are spatially associated with uranium mineralization, have $\delta^{34}\text{S}$ values that can be modelled by a mixing of two reservoirs: 1) a basement fluid in equilibrium with basement sulphides, and 2) a basin fluid containing a component of Proterozoic seawater. Late sulphides and sulphates have a large range of $\delta^{34}\text{S}$ values indicative of varying redox conditions within the basin and a component of sulphur from Phanerozoic seawater.

developed during the period of re-activation and fracturing of fault zones and subsequent incursion of low-temperature meteoric waters into the Athabasca Basin.

The lead and sulphur isotopic compositions of the sulphide and sulphate minerals within the Athabasca Basin can be used to elucidate the movement of the late meteoric water within the fault zones in areas of uranium mineralization and to give an estimate of the magnitude of the interaction between the late, oxidizing meteoric waters and the early-formed uranium. At McArthur River and Eagle Point, some of the pyrites in late fractures have high $\delta^{34}\text{S}$ values and high $^{206}\text{Pb}/^{204}\text{Pb}$ ratios indicating that the meteoric waters associated with the pyrite had a high content of radiogenic lead derived from uranium alteration which occurred during late-stage uranium remobilization (Figure 7). At Key Lake, the late sulphides and sulphates have $\delta^{34}\text{S}$ values similar to some of the sulphides from McArthur River, indicating similar

redox conditions, but at Key Lake the lead isotopic ratios are relatively non-radiogenic (Figure 7). The high $\delta^{34}\text{S}$ values and high $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of the sulphides in late fractures suggest that the late meteoric waters at McArthur River and Eagle Point have interacted extensively with the uranium mineralization late in the paragenesis of the Athabasca Basin, resulting in large-scale lead loss from the uranium. At Key Lake, the combination of low and variable $\delta^{34}\text{S}$ values and low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios within the sulphide and sulphate minerals indicates that relatively little modification to the uranium ores by late-stage meteoric waters has occurred since its formation.

Carbon and Oxidation-Reduction Reactions

The close spatial association of graphite and bituminous material with uranium in many deposits in the Athabasca Basin has led to models that re-

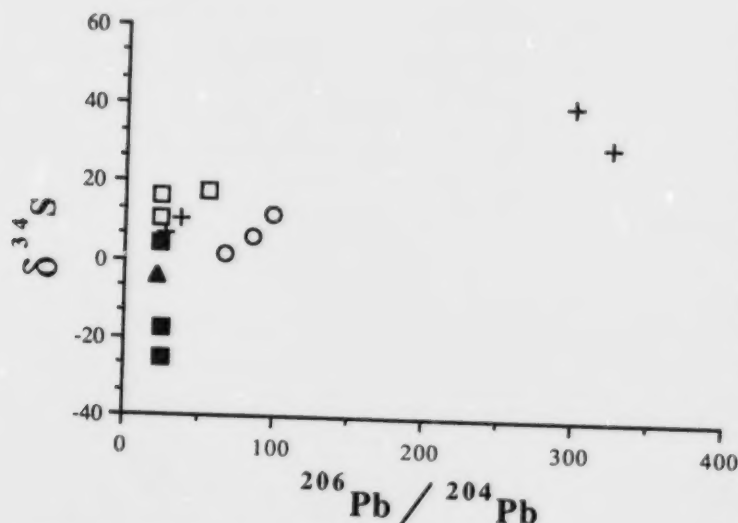
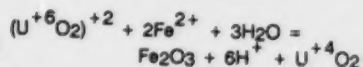


Figure 7 - $\delta^{34}\text{S}$ values and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of sulphide and sulphate minerals occurring in the Athabasca Basin. High $\delta^{34}\text{S}$ values and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios in pyrites from late fractures at McArthur River and Eagle Point indicate extensive interaction of meteoric fluids with uranium. Variable $\delta^{34}\text{S}$ values and low $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of sulphides at Key Lake indicate similar redox conditions, but relatively little interaction of the meteoric fluids with uranium. ($\blacktriangle$) galena clasts at Key Lake; ($\circ$) millerite and gersdorffite within Ni-Co-As-S pods at Key Lake; ($\square$) lead sulphates in sandstones at Key Lake; ($\blacksquare$) late-formed sulphides at Key Lake; (+) late-formed sulphides at McArthur River and Eagle Point.

quire the alteration of graphite to form methane, which then acts as a reductant for uranium deposition (Hoeve and Quirt, 1984; Hoeve and Sibbald, 1978; Bray *et al.*, 1988; Landais *et al.*, 1987). A systematic study of the graphite from altered and unaltered gneisses and associated bituminous material occurring within the Key Lake uranium deposit has been completed by Kyser *et al.* (1988). The results of the carbon isotopic study indicates there is no significant differences among the $\delta^{13}\text{C}$ values of altered and unaltered graphites, and most of the hydrocarbon buttons which surround the deposit. Since the volume of methane required to reduce the uranium around the deposits would be substantial and methane is very depleted in ^{13}C relative to co-existing graphite, significant enrichment of ^{13}C should occur in altered graphite. The carbon isotope data from Kyser *et al.* (1988) did not reveal a ^{13}C -enrichment in the $\delta^{13}\text{C}$ values of the altered graphites relative to the unaltered graphites, nor a lowering of the $\delta^{13}\text{C}$ values in most of the hydrocarbon buttons that presumably formed from condensation of the graphite, thereby implying no significant formation of methane due to alteration of the graphites. Rather, Kyser *et al.* (1988) suggest that the similarity in the $\delta^{13}\text{C}$ values between the altered and unaltered graphite is due to oxidation of graphite producing CO_2 or to radiolysis of graphite. The similarity of the $\delta^{13}\text{C}$ values in the altered and unaltered graphites in

the vicinity of major faults suggests graphite alteration by the oxidizing basin fluid, which was focussed along the faults that preferentially developed in the graphitic zones (Kyser *et al.*, 1988).

Hematite is also spatially associated with the uranium mineralization. Oxidation of Fe^{2+} to Fe^{3+} may be viewed as an alternative agent for the reduction of uranium carried in the oxidizing basinal fluids. A redox reaction between $\text{Fe}^{+2}/\text{Fe}^{+3}$ and $\text{U}^{+6}/\text{U}^{+4}$ can be written as:



This reaction helps explain the association between reduced uranium, and an adjacent hematite zone surrounding the uranium mineralization. Existence of relatively stationary redox fronts producing uranium mineralization at specific sites within the Athabasca Basin (Hoeve and Quirt, 1986) probably developed where fluid mixing occurred. The Fe^{2+} , possibly derived from the breakdown of sulphides and Fe-Mg silicates in the basement, would be carried by the reducing basement fluid and U^{6+} by the oxidizing basinal fluid. A similar scenario has been proposed recently for the uranium, platinum, palladium, gold association in the Nicholson Bay Area (Peiris and Parslow, 1987).

Age Relations

The wide range of ages obtained from uranium mineralization and sediments reflects the complex history of fluid evolution in the Athabasca Basin. Rb-Sr ages of 1630 Ma to 1350 Ma from mudstones and clay pebbles within the Athabasca sandstones and weathered regolith in the basement rocks (Armstrong and Ramaekers, 1985; Fahrig and Loveridge, 1981; Ramaekers and Dunn, 1977) are thought to represent the age of initial deposition and diagenesis of the sediments. These ages overlap the U-Pb ages of 1406 to 1250 Ma from uranium mineralization (Cumming and Rimsaite, 1979; Hoendorf *et al.*, 1985; Ruhrman and Von Pechmann, 1989; Carl *et al.*, 1988). The age of 1406 Ma from uraninite at Key Lake may indicate the first stages of emplacement of uranium early in the development of the Athabasca Basin.

Illites from a number of deposits within the Athabasca Basin have been analyzed for their chemical com-

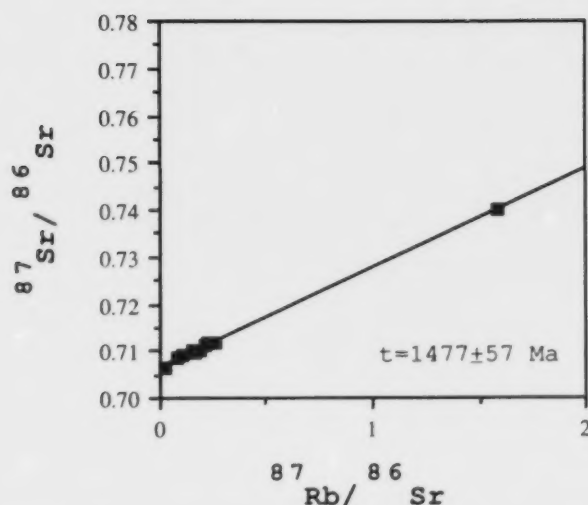


Figure 8 - Rb-Sr isochron of diagenetic illite from various locations in the Manitou Falls sediments having an age of 1477 ± 57 Ma and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7064. This age is believed to represent the age of large scale fluid movements in the Athabasca Basin resulting in the diagenesis of the Athabasca sandstones.

positions, δD and $\delta^{18}\text{O}$ values and K-Ar and Rb-Sr isotopic ratios. Illites within the diagenetically altered Manitou Falls Formation adjacent to and within the uranium deposits yield an Rb-Sr isochron age of 1477 ± 57 Ma and an initial intercept of 0.7064 (Figure 8). These illites generally have low Rb-Sr ratios that reflect the ubiquitous presence of goyasite in these samples, but SEM examination reveals that the goyasite and illite formed contemporaneously so that the Rb-Sr systematics reflect the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and age of the basinal fluid that produced them. The age of the illites indicates that large scale fluid flow and diagenesis within the Manitou Falls Formation predates formation of the unconformity-type uranium mineralization. Thus, sufficient time was available for the oxidizing basinal fluids to leach significant quantities of uranium from the sedimentary sequences to form the uranium deposits.

The strontium isotope systematics of illite and tourmalines within the sediments and basement rocks of the Athabasca Basin can be used to estimate the timing of tourmaline formation (Figure 9). Illite within the basement and the basin have quite different initial strontium isotopic compositions indicating that they formed from two isotopically distinct fluids. Petrographic relations indicate that illite in the Athabasca Basin was affected by fluid events and, since illite has the highest Rb-Sr ratios of all minerals in the basin, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of all but the first diagenetic fluid would have been controlled by the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the illites. Because tourmalines contain very little rubidium, they will have relatively

flat strontium evolution patterns, the intersection of which with the strontium evolution line of the illite in the basin and basement can be used as an indication of the minimum ages of the dravite. Minimum ages of approximately 1300 Ma and 800 Ma for the early and late stages of dravite, respectively, are obtained with this model (Figure 9). The age of the early dravite approximately coincides with the age of uranium mineralization. The similarity between the calculated δD and $\delta^{18}\text{O}$ values of the fluids in equilibrium with diagenetic illite and early dravite also suggests formation from the oldest basinal brines (Figures 3 and 5). The later dravite, with calculated δD and $\delta^{18}\text{O}$ values similar to the fluids that deposited the late kaolinite and uranium in fractures (Figures 3 and 5), has a younger age which may be interpreted as the beginning of uplift within the basin, which resulted in the retrograde alteration of the uranium deposits.

CONCLUSIONS

Between the time of formation of the Athabasca Basin and the present day, the basin has undergone a series of structural and geochemical changes. A major event is associated with the formation of the unconformity-type uranium deposits as a result of mixing of two fluids at the intersection between the unconformity and basement faults. A fluid mixing model has been developed from the isotopic and geochemical characteristics of the alteration minerals within the hydrothermal alteration halos in both the basement and basin rocks (Figure 10a). The model shows that uranium and sulphide deposition resulted from the mixing of a reducing fluid that issued from the basement along faults associated with graphitic units, and an oxidizing, basinal fluid that formed due to extensive interaction of Proterozoic meteoric water with minerals in the sandstones in the basin. An age of 1477 ± 57 Ma, obtained from the diagenetic illite, pre-dates the oldest uranium and indicates that a hydrothermal system operated within the Athabasca sandstones for some time before uranium mineralization occurred.

Subsequent alteration of clay minerals and uranium by a low-temperature meteoric water, which is recorded by the isotopic compositions of late kaolinite, dravite, pyrite and some clay minerals in fractures within the ore zones associated with remobilized uranium (Figure 10b), is a result of late reactivation and fracturing of early fault zones hosting the uranium deposits. This late, low-temperature meteoric water event has ultimately determined the preservation state of the original uranium mineralization, and minerals within the hydrothermal alteration zones, in the unconformity-type uranium deposits.

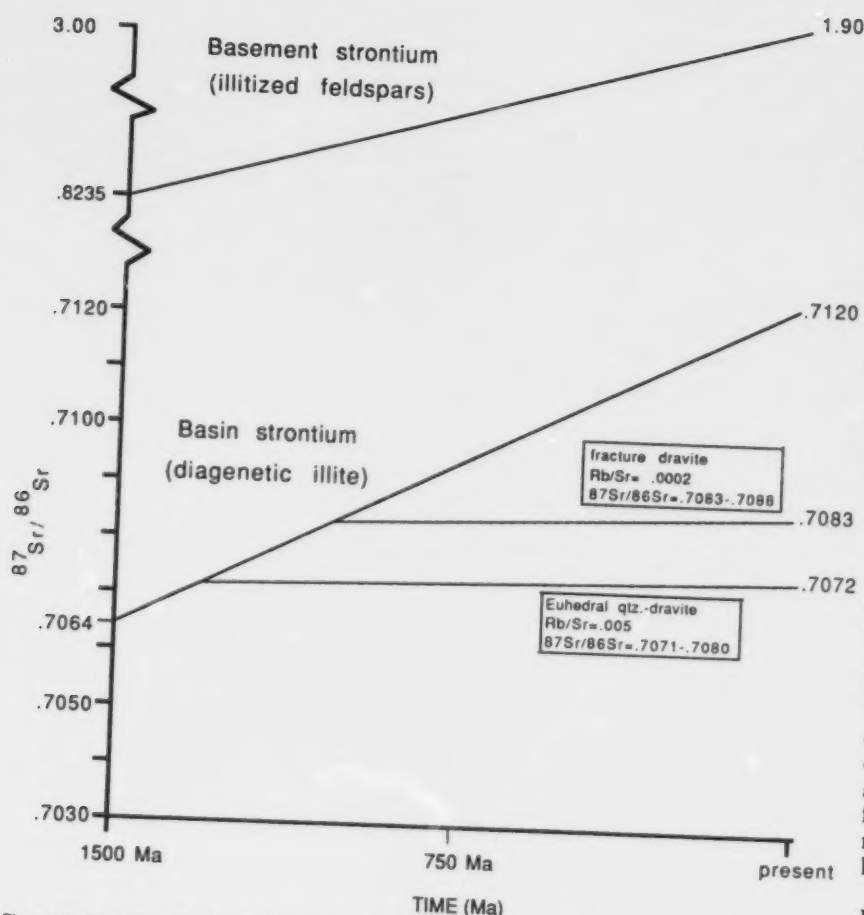


Figure 9 - Evolution of strontium in the Athabasca Basin calculated by using the $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{87}\text{Rb}/^{86}\text{Sr}$ ratios of illitized feldspars in basement rocks (representative of basement strontium), diagenetic illite in the sandstones (representative of basin strontium), and early and late stage dravite. Minimum model ages of formation for the dravite are determined by the intersection between the basin strontium evolution line and dravite evolution lines. Using this method, dravite associated with euhedral quartz has a minimum age of 1300 Ma, and late dravite in fractures has a minimum age of 800 Ma.

Stable and radiogenic isotopic analysis of the clay minerals, silicates, sulphides and carbonaceous materials associated with the diagenesis and hydrothermal alteration of the sedimentary rocks has been used to determine an overall time-temperature-fluid flow model within the Athabasca Basin. As a result, certain isotopic values from the various minerals have potential as guides for uranium exploration. Because an isotopically distinct reducing basement fluid has been recognized, it is possible to identify areas where fluid mixing occurred along fault trends where the basinal fluids are primarily responsible for development of hydrothermal alteration zones. Identifying the fluid mixing zones is critical be-

cause they represent areas where uranium reduction and deposition may occur.

Kyser *et al.* (1988) show that hydrocarbon buttons which are directly associated with uranium ore at Key Lake have low $\delta^{13}\text{C}$ values (approximately -50 per mil) whereas similar bituminous materials near uranium mineralization have similar $\delta^{13}\text{C}$ values to the altered and unaltered graphites. The low $\delta^{13}\text{C}$ values of the hydrocarbon buttons are attributed to the radiolysis and hydrolysis of water and graphite intimately associated with uranium. The occurrence of hydrocarbon buttons with low $\delta^{13}\text{C}$ values may be indicative of substantial uranium concentrations since a sustained radioactive flux over time would be required to produce the low $\delta^{13}\text{C}$ values.

Late fracture development within the Athabasca Basin has resulted in substantial interaction between low-temperature meteoric waters and the surrounding sediments (Figure 10b).

This event resulted in late-formed kaolinite with low δD values and remobilized uranium being deposited in the fractures. The extremely low δD values of the kaolinites within these highly fractured zones in the Athabasca Basin indicate large-scale fluid movements of late, oxidizing waters which have possibly resulted in significant destruction of the early-formed uranium mineralization. The low δD values for the kaolinites and associated clay minerals in the fractured areas may be used to identify areas in the Athabasca Basin that have a poor potential to host economic accumulations of uranium mineralization.

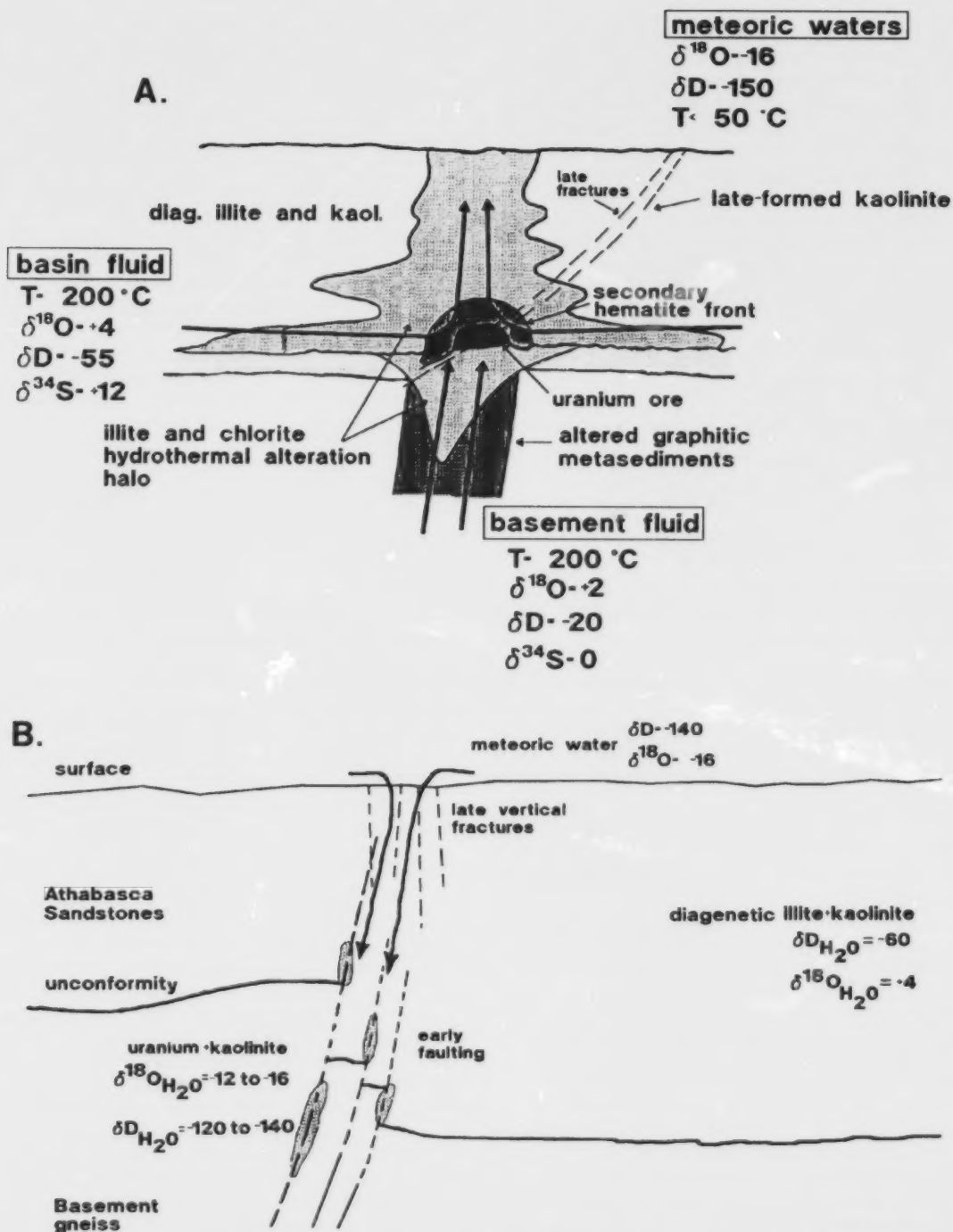


Figure 10 - Diagrams showing the isotopic compositions and flow directions of fluids associated with uranium deposit formation and destruction. A) Fluids associated with formation of unconformity-type uranium deposits involve mixing of a reduced basement and oxidized basin fluids as determined by the isotopic compositions of Mg-chlorite, illite, fluid inclusions in euhedral quartz, and sulphides. B) Later incursion of meteoric water along re-activated faults into the Athabasca Basin resulted in the formation of late kaolinite with remobilized uranium in fractures. The alteration is permeability controlled, and is restricted mainly to the fault zones and surrounding sediments. The extent of isotopic alteration of the minerals by meteoric water decreases away from these permeable zones.

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ACKNOWLEDGEMENTS

The authors would like to thank V. Sopuck, G. Wuhrmann, J. Marlatt, and B. McGill for geological assistance and D. Pezderic for technical assistance provided during the course of this research. Project is funded by a University/Industry grant from NSERC and Cameco.

STRATIGRAPHY OF THE ATHABASCA GROUP SANDSTONE USING NUCLEAR WELL LOGGING: ITS APPLICATION TO URANIUM EXPLORATION IN SASKATCHEWAN

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ABSTRACT

The Athabasca sandstone on the eastern part of the basin belongs to the Manitou Falls Formation of continental origin. The sandstones are monotonous and lack good stratigraphic markers that would allow stratigraphic correlations from hole to hole. In 1986, P. Ramaekers in a special study for the Cigar Lake Joint Venture, indicated that detailed lithofacies analysis allows us to identify at least 3 stratigraphic markers within the Manitou Falls Formation, corresponding to contacts between stratigraphic units of regional extent. However, detailed lithofacies analysis is time consuming and inevitably varies between geologists.

Probing data give objective and unbiased information. It can be shown from diamond drilling data on the Cigar Lake and Close Lake properties that neutron-neutron, gamma-gamma and resistivity logs allow a clear and precise identification of the main stratigraphic markers of the Manitou Falls Formation. The best results are obtained from reduced scale (1:2000) and filtered logs where the contrasted signature of each unit is enhanced. Stratigraphic markers can be easily recognized from resistivity logs but, unfortunately, these may only be obtained in open holes, and heavy fracturing and alteration prevent in most cases logging of the hole down to the unconformity. In practice, the neutron-neutron logs which give comparable information have been used because the data is available for all holes. The stratigraphic markers are identified by a qualitative analysis of the response: background value, curve shape, peak amplitude, peak density and curves matching with well documented holes. Several cross sections are presented through the Close Lake and Cigar Lake properties to illustrate the usefulness of stratigraphic correlations at regional and local scales.

Exploration for Key Lake-Cigar Lake type uranium deposits in areas of thick sandstone cover (350-700m) is very expensive and the information of each drill hole has to be maximized. Recent progress in ground geophysics and a better understanding of geochemical alteration haloes have modified substantially our drilling strategy, the regional approach being favoured. In recent years, exploration for blind Athabasca uranium deposits has been frequently carried out through widely spaced drilling of pluri-kilometric electromagnetic basement conductors. Stratigraphic correlations between holes provide information on post-Athabasca and syn-sedimentary faulting, both of which are important controls for fluid circulation and uranium deposition. Furthermore, the neutron log provides information on fracturing and clay alteration haloes. Alteration haloes around Athabasca uranium deposits are usually large and clearly identified from lithogeochemical analysis (U, K, Al and, in some cases, trace elements). However, uranium, trace element content and clay composition as indicated by the K/Al ratio vary with the stratigraphy of the Manitou Falls Formation. The MFd member is generally low in uranium with illite-rich clay. On the other hand, the MFb member at the base of the formation has higher uranium content and low K/Al ratio indicative of a kaolinite-rich clay. Sandstone stratigraphy is therefore essential to the definition of proper threshold values for tracers of mineralization and alteration haloes.

Long term applications of well multi-parameter logging in the Athabasca Basin is foreseen when non-coring drilling techniques will be used in exploration (top 300 to 500m of sandstone) and/or for the delineation of mineralized zones.

MINERAL POTENTIAL MODELLING WITH A GEOGRAPHIC INFORMATION SYSTEM

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ABSTRACT

Geographic information systems not only supply the tools for building and accessing a multi-map geoscientific database, they can also provide the computing platform for developing and testing mineral potential models. In general, such models are algorithms for combining multiple input maps (geology, geophysics, geochemistry) to produce an output map of mineral potential, in some cases with an associated uncertainty map.

In relatively well-explored regions, with an abundance of known mineral showings, predictive mineral potential modelling can use either regression techniques or a new Bayesian method known as 'weights of evidence' modelling. For example, gold potential in the Meguma terrane, Nova Scotia has been mapped by combining weights of evidence from lithology, distance to contacts and structures, with lake-sediment and biogeochemical signatures. Areas where the estimate of mineral potential is uncertain are masked out. The model not only predicts all the important gold districts, but also shows when areas of high potential occur with no known mineralization.

For the Star Lake area, with too few sites of known mineralization for statistical predictive modelling, expert opinion can be used to generate a series of trial models. The 'weights of evidence' framework can still be used, but instead of measuring the overlap relationships of known occurrences with the predictor maps, the expert is asked to estimate these relationships.

The modelling language and interactive graphical display of the geographic information system facilitate the experimentation with a variety of models. These experiments yield a series of mineral potential maps; the maps are neither 'right' nor 'wrong', but simply products of the assumptions, similar to Chamberlin's multiple working hypotheses, and aid the exploration process.

Diamond Exploration

THE NATURE OF KIMBERLITES, LAMPROITES AND LAMPROPHYRES

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EXTENDED ABSTRACT

Kimberlites, lamproites and some lamprophyres are all now known to be primary sources of diamond. For exploration purposes it is important to be able to determine rapidly to which clan a given potentially diamondiferous rock belongs. This problem is in some instances not trivial as on a simple petrographic basis many rocks belonging to different clans are similar. Identification of the correct petrological lineage is important as exploration techniques for kimberlites and lamproites are different.

Recent mineralogical and isotopic studies have shown that there exist two varieties of kimberlite:

Group 1 or megacryst-bearing olivine-rich monticellite-serpentine-calcite kimberlites.

Group 2 or micaceous kimberlites

Group 1 and 2 kimberlites are complex hybrid rocks consisting of minerals that may be derived from (1) the fragmentation of upper mantle xenoliths, (2) the megacryst or discrete nodule suite and (3) the primary phenocryst and groundmass minerals. The contribution to the overall mineralogy from each source varies widely and significantly influences the petrographic character of the rock. Further modal variations result from differentiation processes. The characteristic inequigranular texture of group 1 kimberlites results from the presence of megacrysts (> 10mm) and macrocrysts (0.5-10mm) set in fine grained groundmass. These minerals are of cryptogenic origin and consist of olivine, Mg-ilmenite, pyrope, Cr-diopside and enstatite. The principal primary minerals found include olivine, phlogopite, spinels, perovskite, apatite, monticellite, calcite and serpentine.

Key mineralogical features essential for the recognition of group 1 kimberlites include the presence of:

1) The megacryst suite, especially Mg-ilmenite (MgO 3-23 wt%, typically > 8 wt%), Cr-poor (0-3 wt% Cr₂O₃) titanian pyrope (G1, G2 garnets), and subcalcic diopside.

2) Ti-poor (< 1 wt% TiO₂) phlogopites that range in composition from phlogopite to eastonitic phlogopite and Ti-poor tetraferriphlogopite.

3) Spinel that range in composition from titanian magnesian aluminous chromite to magnesian ulvospinel-magnetite.

Characteristically absent from group 1 rocks are aluminous diopside, feldspars, amphiboles, leucite and melilite. Mantle derived xenocrysts of magnesian aluminous chromite, Cr-diopside and Cr-pyrope (G9, G10) are common. Some group 1 kimberlites bear a superficial petrographic resemblance to olivine lamproites.

Group 2 kimberlites (or orangeites) consist principally of rounded olivine macrocrysts set in matrix which consists of microphenocrysts of phlogopite and diopside, together with spinel, perovskite, and calcite. K-Ba-V titanates belonging to the hollandite group are characteristic accessory phases. Key mineralogical features of these rocks are:

- 1) A complex hybrid assemblage of microphenocrystal Ti-poor phlogopites.
- 2) Spinel which range in composition from titanian magnesian chromite to ulvospinel-magnetite.
- 3) The presence of complex Zr and Ti-based minerals e.g. kimzeyitic garnet, hollandites.

Notably absent from group 2 kimberlites are monticellite, serpophitic serpentine, magnesian ulvospinel and the megacryst suite of Mg-ilmenite and Ti pyrope. Group 2 kimberlites appear to be found only in the Kapvaal craton and represent a unique manifestation of continental lithospheric magmatism. Some micaceous kimberlites are petrographically similar to minettes and phlogopite lamproites. They may be easily distinguished from these rocks on the basis of phlogopite compositional trends and the characteristic presence of feldspar and/or leucite. Group 2 kimberlites may contain mantle-derived xenocrysts of Cr-pyrope (G9, G10).

Lamproites are a clan of rocks of very diverse petrographic character. Major primary minerals commonly present include Al_2O_3 -poor (5-12 wt%) Ti-rich (2-12 wt% TiO_2) phlogopite and tetraferriphlogopite, potassian titanian richterite, forsteritic olivine, Al-poor diopside, sanidine and leucite. Typomorphic minor and accessory phases include enstatite, priderite, apatite, wadeite, magnesiochromite, titanian magnesian chromite, shcherbakovite, amalcolite, perovskite, jeppeite and barite. Key mineralogical features for the recognition of lamproites include the presence of:

- 1) Phlogopites that evolve from Ti-phlogopite to Al-poor Ti-tetraferriphlogopite.
- 2) Na-Al-poor (< 1 wt% Al_2O_3 , Na_2O) diopside, K-Ti-richterite (3-5 wt% TiO_2 , 4-6 wt% K_2O) Na-poor (< 1 wt% Na_2O) Fe-rich (1-5 wt% Fe_2O_3) sanidine, non stoichiometric Fe-rich (1-4 wt% Fe_2O_3) leucite, wadeite ($K_4Zr_2Si_6C_{18}$), priderite $\{(K,Ba)_{1-2}(Ti,Fe)_{6-7}O_{16}\}$.

Notably absent from lamproites are megacrystal Mg-ilmenite and Ti pyrope. Some olivine lamproites are similar in petrographic character to group 1 kimberlites. The two rocks are easily distinguished on the nature of the spinel and phlogopite compositions and by the common presence of groundmass amphibole in the lamproites. Lamproites may contain mantle-derived chromite and Cr-pyrope xenocrysts.

The term lamprophyre encompasses rocks of diverse petrographic character and origin. The term is useful as a field term for rocks of uncertain character but has no petrogenetic significance. Kimberlites and lamproites are NOT members of the lamprophyre group. Many lamprophyres are directly related to other petrological groups e.g. camptonites, monchiquites and sannaites to the basalt clan, alnoites, aillikites and alvikites to the melilitite clan. Only minettes bear some superficial petrographic similarity to phlogopite lamproites. They may be distinguished easily from the latter on the basis of the composition of phlogopite, feldspar and pyroxenes.

Kimberlites and lamproites differ considerably in their volcanic style. Kimberlites typically form diatremes composed of volcanoclastic breccia and extrusive and/or pyroclastic activity is rare. In contrast lamproites form shallow volcanic vents. Lavas flows and pyroclastic deposits are characteristic.

EXPLORATION FOR DIAMONDIFEROUS KIMBERLITES & LAMPROITES

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ABSTRACT

Diamonds are recovered mainly from kimberlites and to a lesser extent from lamproites. They occur as xenocrysts brought up from the mantle by kimberlites or lamproites. Of more than 2,000 known kimberlites only about 50 have been economic and of these only about 15 have been major producers. Only one economic lamproite is known.

Kimberlite pipes range up to 216 ha in size and generally occur in clusters of up to 50 in number and with diameters of the cluster up to 50 km. Generally kimberlite emplacement does not have obvious near surface structural controls.

Techniques used in exploration for diamond pipes consist mainly of heavy mineral sampling and airborne or ground magnetics. Other successful techniques used include prospecting, remote sensing, geochemistry, gravity, seismic, electromagnetics and induced polarization.

The use of mineral chemistry with analysis by electron microprobe is now being increasingly used to infer favourable conditions for the presence or preservation of diamonds. Once a diamond host has been found, microdiamond analysis of small samples can be used as a general indicator of macrodiamond potential.

Although an economic diamond mine has not yet been found to date in North America the chances are considered excellent for such a discovery in the next decade.

INTRODUCTION

Diamonds have been treasured by mankind for over 3000 years - originally as an object of rare beauty - more recently because of their extreme scientific curiosity. World production of natural diamonds in 1988 was 98.73 million carats compared to 15.5 million in 1950. This represents a 14 percent per annum growth rate. Diamonds are produced from 20 countries (Table 1) of which Australia, Botswana, South Africa, the Soviet Union and Zaire are the major producers. Botswana (1989 production value was US\$1.33 billion), South Africa and Russia are the foremost producers in terms of value.

Diamonds are found in mantle-derived igneous rocks with the principal hosts being kimberlite and lamproite. Secondary diamond deposits, such as the marine deposits of Namibia, are derived by weathering of the host followed by transportation and con-

centration at favourable localities. Also mined are eluvial concentrations over low grade pipes, e.g. Mbuji Mayi, Zaire.

Of approximately 2,000 known kimberlites in the world, less than 50 can be considered commercial. There have been less than 15 major primary producers with, surprisingly, only five major (+ 3 million carats per annum) discoveries made in the last 50 years. These are Orapa and Jwaneng in Botswana, Argyle - a lamproite in Australia, Mir in Siberia and the Venetia Pipe in South Africa (scheduled for full production in 1994).

Diamonds rank very high in value of world production. In 1984 diamonds were fifth after Fe, Au, Cu and Zn but ahead of Ni, U, Pt, Pb and Ag.

Table 1 - World Rough Diamond Production 1983-1988 (million carats)

	1983	1984	1985	1986	1987	1988
Australia	6.2	5.7	7.06	29.2	31.0	35.0
Zaire	13.0	18.5	19.6	20.5	24.0	23.0
Botswana	10.7	12.9	12.6	13.0	13.0	15.0
USSR	12.0	12.0	12.0	12.0	12.0	12.0
South Africa	10.0	9.8	9.9	10.2	11.0	9.0
Namibia	0.96	0.93	0.91	1.0	1.0	0.9
South America	1.0	1.0	0.85	0.85	0.85	0.85
Ghana	0.8	0.33	0.6	0.55	0.6	0.3
CAR	0.3	0.3	0.5	0.6	0.6	0.45
Sierra Leone	0.3	0.42	0.4	0.4	0.45	0.3
Liberia	0.4	0.4	0.4	0.3	0.35	0.35
Tanzania	0.37	0.36	0.35	0.3	0.20	0.13
Angola	1.0	0.92	0.9	0.2	0.9	1.0
Other Countries	0.2	0.29	0.47	0.5	0.6	0.45
WORLD TOTALS	57.23	63.85	66.45	89.6	95.95	98.73

KIMBERLITES

Kimberlites remain the main source of diamonds. They are complex potassic ultramafic rocks varying from sedimentary-looking epiclastics, through breccias, to inequigranular or aphanitic-textured hypabyssal facies rocks. Mitchell (in press) gives a detailed review of kimberlites and lamproites so only pertinent details relevant to exploration will be given here. Kimberlites occur as diatremes, dykes, or sills. They are divided into Group 1 megacryst-bearing olivine-rich kimberlites and Group 2 or micaceous kimberlites. Group 1 kimberlites have a megacryst/macrocryst assemblage of picroilmenite, Cr-poor titanite pyrope and subcalcic diopside as well as phlogopite and a variety of spinels. These commonly have abundant xenocrysts of chrome pyrope, chrome diopside and magnesian chromite. Group 2 kimberlites, known so far only from South Africa, lack the megacryst suite found in Group 1. They occur mainly as thin dykes, many of which are very rich in diamonds. Examples of Group 2 diatremes are Finsch and Dokolwayo (Swaziland). The absence of ilmenite makes their detection in covered areas by heavy mineral sampling more difficult.

Kimberlites occur in clusters of three to 50 or more pipes with diameters of the clusters ranging up to 50 km. Individual clusters tend to have one or more larger pipes. The larger pipes in a cluster are generally more likely to be economic than the smaller pipes. It is very unusual for more than one pipe in a cluster to be economic. Only two clusters - Kimberley with five mines (Figure 1) and Orapa with two mines - are known to contain more than one commercial pipe.

Sizes of pipes vary from less than 0.4 ha to 216 ha. Typical sizes and shapes are shown in Figure 2. They are generally round to oval in shape but can be much more elongate. Pipes are mined both as open pits or by underground mining. The Kimberley pipe (South Africa) was mined to a depth of 1073 m. An announcement has just been made that the de Beers Mine (South Africa) will close after 120 years of production. Large (+ 50 ha) pipes are particularly suited to low cost open pit mining with a strip ratio for the 50 ha mine at Jwaneng (Botswana) estimated to be less than 0.6 to one (waste to ore). A 100 ha mine generates 2.6 million tons per vertical metre so is eminently amenable to high mining rates. At Orapa (Botswana) mill throughput is 20,700 tons per

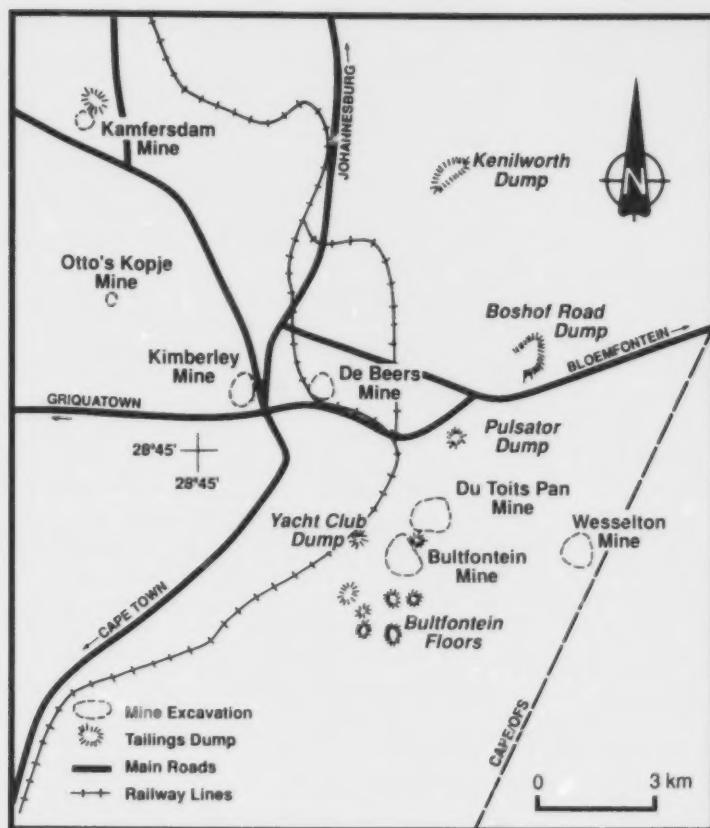


Figure 1 - Plan showing the distribution of diamond mines and old dumps in the Kimberley area - South Africa.

day (7,258,000 tons per annum) while at Jwaneng it is 16,500 tons per day or 5,783,000 metric tons per annum. The narrow widths of kimberlite dyke mines (widths commonly less than one m) require labour intensive high cost mining methods. The higher grade and good quality diamonds commonly found in South African dyke (fissure) mines offset the higher costs.

AGES

Ages of kimberlite pipes range from Archean to Tertiary. Producing pipes range in age from to 1200 million years [Ma] (Premier, South Africa), 1100 Ma for Sierra Leone pipes, 342 Ma for Mir (USSR), 150 Ma for Finsch (South Africa), 90 Ma for Kimberley (South Africa) to 41 Ma for Mwadui in Tanzania with many more of intervening ages. Some knowledge of the expected age of pipes is thus vital in planning an exploration programme for diamonds. Search for older age pipes in a thick sequence of younger sediments would obviously be a waste of time and money.

If the apparent tendency, as seen in Siberia and Southern Africa, of economic diamondiferous pipes to occur towards the centre of the sub-continent is projected to the North American stable platform then Saskatchewan, Manitoba, Ontario and a number of central states in northern U.S.A. should be prime targets for kimberlite exploration.

GENESIS OF DIAMONDS

Diamonds range in size from a few microns to the Cullinan diamond which weighed 3106 carats (0.62 kg). They were formerly thought to have crystallized within kimberlite as a phenocryst phase. Age dating by Richardson *et al.* (1984), and Kramers (1979) has shown that diamonds in 90-100 Ma age pipes are about 3300 Ma. Hence diamond is clearly a xenocryst sampled during ascent of the kimberlite from depths in the upper mantle which lie within the diamond stability field. Studies of minute inclusions in diamonds indicate mutually exclusive peridotitic and eclogitic suites co-existing with diamonds. Nothing is known about the distribution of diamond-bearing peridotitic and eclogitic material at depths of the order of

150 km. Hence it is extremely difficult to predict whether a pipe will sample economic quantities of diamond or not.

Grades of economically viable diamond pipes range from less than four carats per 100 tonnes to 730 carats per 100 tonne. Diamonds are divided into gem, near gem and industrial stones. Percentages of gem plus near gem of total production range from a low of 25% in Liberia, 45% in Australia, 71% in Botswana to 93% in Guinea. A typical pipe may have 20% gem, 24% near gem and 56% industrial diamonds. World production averages about 40% gem plus near gem diamonds with the remaining 60% being of very low value industrial stones.

LAMPROITES

Lamproites are ultrapotassic peralkaline rocks rich in Ba. Diamonds have been found in olivine-bearing lamproites at Argyle and Ellendale in W. Australia, in Arkansas, India and the Ivory Coast (Mitchell, 1990). Lamproite vents, unlike the ice-cream cone-

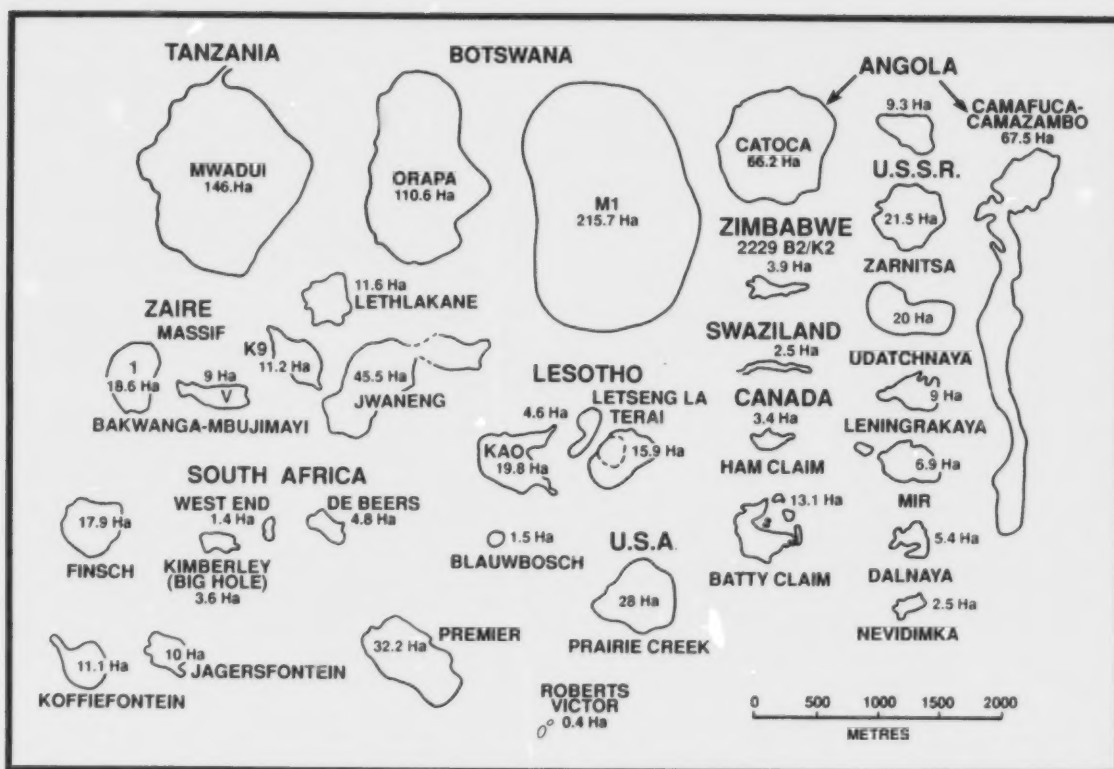


Figure 2 - Shapes and sizes of diamond pipes.

shaped vents of kimberlites, are shaped like a champagne glass. Grades at the Argyle mine are the richest in the world, as much as 730 carats per 100 tons. Quality however is very poor with only 10% being of true gem quality. The average value of diamonds at Argyle is about US\$7.50 per carat compared to an average for Botswana of US\$87.29 and an average estimated value at Venetia of US\$92 per carat.

EXPLORATION FOR LAMPROITES AND KIMBERLITES

Scientific exploration for diamond bearing pipes has doubled the supply of natural stones to the market place since World War II. Large prospective areas remain in the world but are relatively inaccessible because of political reasons, isolation, climate or surficial cover. Despite the great potential for the discovery of economically viable pipes in North America, very little sustained exploration has been carried out partly because of lack of understanding of modern exploration techniques and partly because of the high risk of failure. Diamond discoveries will only be made by those using modern techniques, and those having faith, persistence and courage enough

to continue after years of failure, with management and financial backing to continue their search.

In Soviet Russia a State programme consisting of several hundred prospecting teams commenced work in 1945 in a targeted area of four million km². In 1953 a 0.1 carat diamond was found hundreds of km from its source. In August 1954 the first barren pipe was found and in June 1955 the first payable pipe (Mir) was found. By 1967 about 400 pipes were known with four of them being economic.

In Botswana exploration for diamonds commenced in 1955 and by April 1967 Orapa (production in 1971) was discovered followed shortly thereafter by Letlhakane (production 1975) and in 1973 by Jwaneng (production in 1982). Approximately 130 pipes are now known in Botswana of which about half were found by Falconbridge Limited. The cost of the exploration phase by de Beers in Botswana was US\$1,500,000 up to the discovery of Orapa. Falconbridge spent approximately US\$11,000,000 between 1975 and 1982 to discover and evaluate some of their 65 odd pipes.

In Australia a serious exploration programme resulted in the discovery of the Ellendale lamproite

pipes in 1976 followed by the discovery of Argyle in August 1979 (production end 1985).

It is probable that the North American Craton will yield as many pipes as the Kaapvaal Craton or the Siberian Shield. The widespread presence of kimberlitic minerals and numerous alluvial diamonds in Alaska, Canada, the Great Lakes states, California, Nevada, Washington, Idaho and the Appalachian states points to a high probability of one or more economic pipes being found in North America. In addition, diamond-bearing kimberlites/lamproites are now known from Somerset Island (N.W.T.), Quebec, Ontario, Saskatchewan, Arkansas and the Wyoming-Colorado State Line area. The diamonds found south of the Great Lakes are of good quality and range up to 21.25 carats in weight.

STRUCTURAL CONTROLS

Kimberlite exploration should be concentrated in areas of major continental cratons whose roots contain diamond-bearing lherzolitic or eclogitic horizons. Where kimberlitic xenoliths are available these should be used to define the paleogeotherm which in turn defines an on- or off-craton source. Although kimberlites appear to have deep seated structural controls for their emplacement, the structures are generally not readily apparent. However they typically occur in areas where tensional forces are important - a spatial relationship to diabase dyke swarms or continental type flood basalts is common. Many kimberlites occur on gentle uplifts reflected by regional warps or around great structural basins or have been intruded along the upper hinge of a flexure (Figure 3). These flexures may have an accompanying regional positive gravity expression. In Angola, kimberlites are emplaced along faults or at fault intersections. In Botswana kimberlite emplacement may be controlled by the intersection of regional WNW anticlinoria with earlier NNE antiforms (Pretorius, 1979).

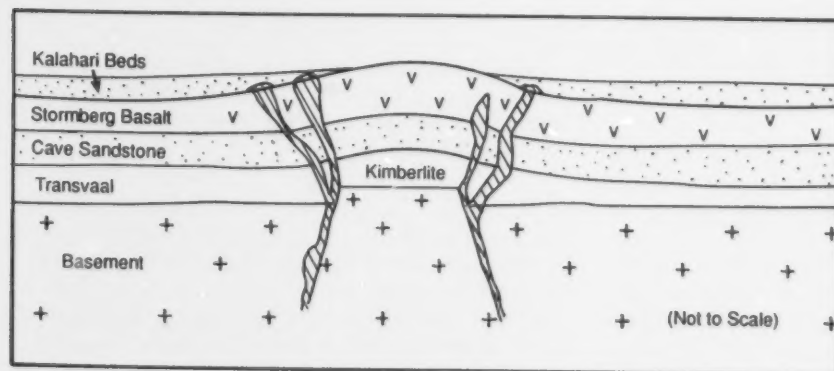


Figure 3 - Distribution of kimberlites around Lethakane Dome, Botswana.

The Mesozoic intrusions in Liberia, Angola, South Africa, Botswana and Brazil seem to be related to the opening up of the Atlantic Ocean and the breakup of Gondwanaland. Marsh (1973) has noted how kimberlites appear to occur towards the centre of the continent along linear extensions of lines of alkalic intrusive activity towards the coast. These zones may be on great circle extensions of transform faults in the ocean.

MODERN TECHNIQUES FOR DIAMOND EXPLORATION

Modern techniques for diamond exploration include the following: prospecting, remote sensing, geochemistry, heavy mineral sampling, heavy mineral chemistry, radiometric surveys and other geophysical techniques. Each of these techniques will be described briefly.

Prospecting

Geological prospecting for exposed kimberlites, particularly in confined areas of abundant exotic rock types, and crustal and mantle rocks is important. Because of the relatively soft and friable nature of kimberlite it is likely that many will ultimately be found to underlie lakes or muskegs in Canada.

Remote Sensing

Kimberlites may be found using air photography, remote sensing, or satellite imagery. The high percentage of clay minerals in kimberlite may give rise to characteristic spectral signatures. The Orapa and Finsch (South Africa) pipes are clearly visible on aerial photographs.

Geochemistry

Kimberlites characteristically have high Ti, Cr, Ni, Mg, Ba, Nb anomalies in overlying residual soils.

Gregory and Tooms (1969) found that significant dispersion patterns occur around the Arkansas lamproites. Caution should be exercised as other alkaline rocks can also give similar geochemical signatures.

Heavy Mineral Sampling

One of the most widely used techniques is heavy mineral sampling. Resis-

tant heavy minerals such as ilmenite, garnet and chromite are commonly sought in stream sediment, esker, basal till, reconnaissance soil, detailed soil, detailed grid loaming or other sampling methods which are tailored to local conditions. Detailed orientation surveys to determine the best type of sampling technique and sample size is required before carrying out a major sampling programme. In Canada, complex transfer of heavy minerals from one till to as many as three younger tills calls for expert knowledge and particular patience in order to decipher the glacial history of the region. The writer believes that ice rafted heavy minerals including chrome diopside may move as much as several hundreds of km.

In South Africa, Botswana and Australia under warm weathering conditions chrome diopside is generally not found more than 10 km from source. In Botswana ilmenites are commonly found less than 20 km from source whereas garnets can be blown by wind for tens of km from source. A distality index can be determined based on ratio of garnet to ilmenite grains.

The surface morphology, i.e. degree of abrasion, roundness, presence or absence of remnants of original surface, remnants of kelyphitic rims on garnets can all be used to determine distance from source in certain areas. Size of grains, as well as numbers present when normalized to a constant weight can also give meaningful results but care should be exercised as many different concentrating mechanisms can give spurious results. In Wyoming chrome diopsides and garnets are known to have gone through a full sedimentary cycle without being destroyed. Afaresev *et al.* (1984) conclude that the mode of transportation has a greater effect on the degree of mechanical wear than the distance from the source. In Wisconsin pyrope garnets and probably diamonds appear to be weathered out of Cambrian sandstones indicating a pre-Cambrian source. Much has still to be learned about the movement of kimberlitic minerals during Pleistocene glaciation. In the case of lamproites, chromites and diamond, as well as zircon and andradite, are the best heavy mineral indicators.

Extraction techniques have to be extremely efficient as a four grain anomaly from a 20 kg sample represents an accuracy of between one in 10 to one in 40 million.

Diamond would be the best indicator of all because of its extreme hardness and its known ability to be transported fluvially for at least 1200 km. However the average grade of a South African pipe is about 200 times less than the average grade of a Canadian gold mine whereas ilmenite and garnet occur in num-

bers which are orders of magnitude more abundant than diamond.

Heavy Mineral Chemistry

The electron microprobe has revolutionized kimberlite exploration and routine 'probing' of kimberlitic minerals is now carried out by most companies. Following Sobolov (1977) and Gurney (1984) it is now well known that the presence of subcalcic high Cr 'G.10' garnets similar to those found as inclusions in diamonds can be an excellent indicator of a deep mantle tapping kimberlite which has a high probability of carrying diamonds. Similarly +60% Cr₂O₃ chromites with compositions resembling diamond inclusion chromites are good indicators of diamond potential. However, there are always exceptions to the rule, for example the Zero pipe near Kuruman, South Africa. Table 2 shows silicate analyses of typical favourable G.10 garnets in an exploration sample. In eclogitic garnets, high sodium is favourable. Ilmenites are rarely found as inclusions in diamonds. Their composition can indicate the degree of diamond preservation in a kimberlite, i.e. low Fe³⁺ to Fe²⁺ ratios indicate very reducing hence favourable diamond preservation conditions and conversely higher ferric to ferrous ratios are indicative of oxidizing conditions. Economic pipes generally have more than 7% MgO in ilmenites. Chrome versus magnesia plots for ilmenites can be used to predict different kimberlite clusters in exploration samples.

The numbers of diamond inclusion type minerals found in kimberlites can range from nil to 20% of the total present for that mineral. Hence extensive microprobe work may be required to detect diamond inclusion type minerals.

Radiometric Surveys

These should show mica-rich dykes or pipes with little cover.

Geophysics

A variety of geophysical techniques are available, but the most effective methods for diamond/kimberlite exploration include magnetic, gravity, electromagnetics and resistivity.

Magnetics

Magnetic surveys are now fairly widely used for kimberlite exploration. Figure 4 shows a typical magnetic anomaly over a pipe, however, the presence of kimberlite in areas of noisy magnetic background may be difficult or impossible to detect. In addition many pipes are non-magnetic while intrusive plugs of serpentinite, diorite, gabbro, syenite and many other

Table 2 - Diamond Inclusion Type Garnets From An Exploration Sample

SI02	TI02	AL203	CR203	FE0	MNO	NGO	CA0	TOTAL
41.28	0.10	19.37	6.50	6.37	0.30	22.11	3.10	99.13
42.14	0.05	21.19	4.88	5.71	0.24	24.60	1.47	100.28
41.82	0.11	19.73	6.44	6.53	0.32	22.64	2.71	100.30
41.95	0.03	19.63	6.87	6.14	0.28	23.97	1.22	100.09
42.31	0.02	22.41	3.66	6.38	0.34	22.83	2.92	100.87
42.21	0.04	21.10	5.03	6.09	0.28	24.23	1.10	100.08
42.14	0.00	20.61	5.79	6.15	0.28	24.42	1.21	100.60
42.60	0.06	21.12	5.14	6.12	0.28	24.19	1.16	100.67
41.73	0.02	19.71	6.63	6.44	0.32	22.94	2.04	99.83
41.88	0.05	19.32	7.20	6.17	0.30	23.90	1.02	99.84
42.08	0.08	19.91	6.30	6.04	0.25	22.77	2.98	100.41
41.69	0.13	18.66	7.91	6.43	0.35	23.23	2.23	100.63
42.22	0.06	21.14	5.07	6.13	0.30	24.30	1.20	100.42
42.33	0.06	21.29	5.09	6.14	0.28	24.20	1.17	100.56
41.18	0.09	18.42	8.04	6.38	0.30	22.29	2.83	99.53
41.19	0.04	18.12	8.13	6.43	0.35	21.60	3.71	99.57
41.51	0.00	19.48	6.38	6.56	0.39	21.11	3.81	99.24
42.01	0.00	18.98	7.19	6.22	0.27	22.14	3.04	99.85
41.32	0.00	16.61	10.06	6.11	0.32	22.00	3.16	99.58
41.78	0.00	19.83	6.22	6.36	0.32	21.81	3.81	100.13
42.08	0.00	19.25	6.93	6.10	0.31	22.09	3.24	100.00

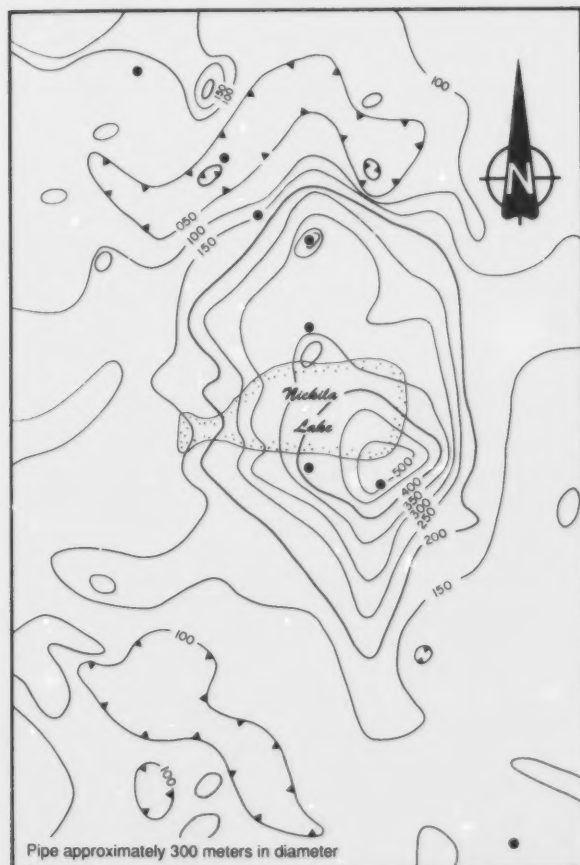


Figure 4 - Ground magnetics over a kimberlite pipe - Ontario.

rock types can give similar signatures. Farmhouses, steel silos, sanitary landfill sites, junk yards and factories can also all give spurious kimberlite-like magnetic signatures. In one area in Botswana less than 25% of boreholes drilled were successful in locating kimberlites using magnetics and other geophysical techniques.

Gravity

Gravity can give excellent confirmatory tests both as to the size of a pipe and to help confirm whether the target is likely to be a kimberlite or not. Figures 5, 6 and 7 show how gravity was able to indicate a much larger pipe than indicated by magnetics alone.

Electromagnetics and Resistivity

In areas of deep weathering, airborne E.M. can be an effective means of locating pipes. Figure 8 shows an INPUT survey flown over a kimberlite at a height of 122 m. Ground E.M. and electrical resistivity have also been used effectively to locate pipe boundaries.

Other Geophysical Methods

Seismics and induced polarization (McNae, 1979) have also been successfully used to locate pipes.

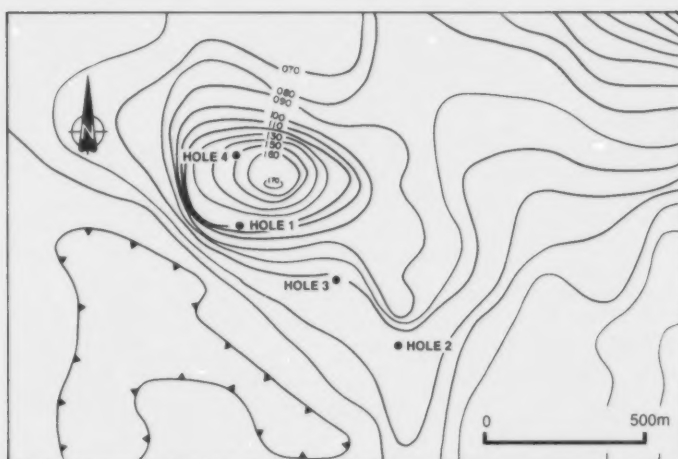


Figure 5 - Ground magnetic survey over a kimberlite pipe.

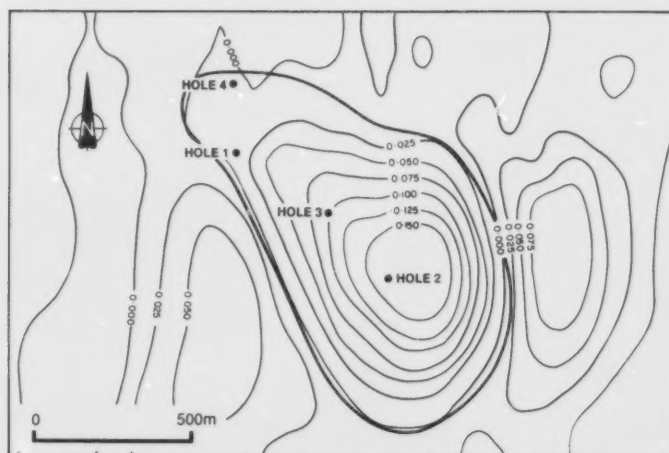
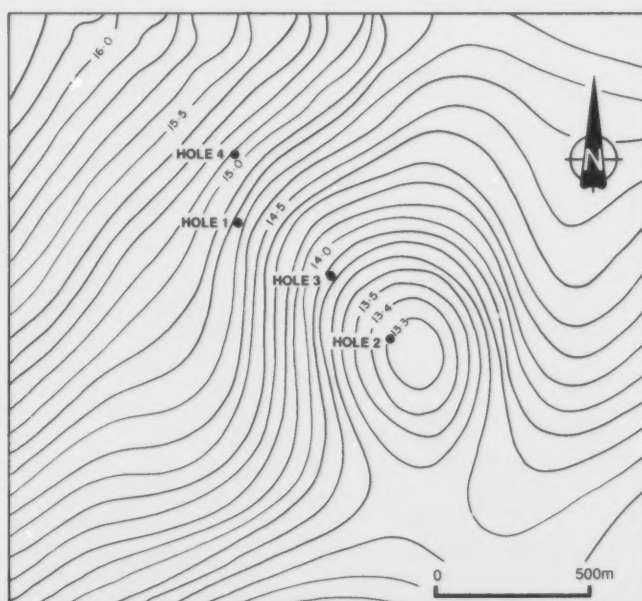
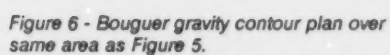


Figure 7 - Bouguer residual gravity contour of same area as Figure 5.

MICRODIAMONDS (MD'S)

Once a pipe has been found, relatively small samples (20 - 100 kg) can be tested for their microdiamond content using some form of dissolution or fusion of the kimberlite. Plotting of either weight or numbers of stones versus stone size can be used to predict size distributions of the macrodiamond population (Figures 9 and 10). In general abundant microdiamonds are necessary for the likelihood of economic pipes, but even very low grade pipes (in terms of macrodiamonds which are greater than 0.5 to one mm) can be economic because of occasional large, high quality, high value stones. These pipes would probably not give high microdiamond counts. Conversely at least one pipe is known to the writer which has high MD counts but has a marked lack of bigger stones and hence a low macrodiamond grade. No barren pipes are known which have high MD contents.

DIAMOND DEPOSIT EVALUATION

Because of the very small amounts of diamond present in an economic pipe and because of the random high values present it is typically very difficult but extremely vital to know the true value of production in the current market. Thus it is very necessary to combine both a highly efficient recovery process with security at the test site. At the evaluation stage the loss of a single high-value stone could negatively affect the evaluation or even render a negative evaluation of the economic feasibility of a pipe. Generally a sample 'parcel' of 5,000 to 10,000 carats may be needed to give both a good idea of the

average value and grade of a pipe. Different rock type phases of a kimberlite can have markedly differing grades so this has to be considered when planning the detailed bulk sampling of a pipe.

WHY EXPLORE FOR DIAMONDS IN NORTH AMERICA?

1. We have the largest craton/stable platform in the world.
2. Relative to Siberia and South Africa it appears that hundreds of kimberlites remain to be discovered.
3. North America is underexplored for diamonds.
4. Large, good quality diamonds have been found as alluvials in North America.
5. A number of areas have favourable mineral chemistry.
6. Working costs of kimberlite open pit mines are very low.
7. Capital costs are no greater than other mines. Tailings are benign and non-acid generating and no harmful chemicals are used during extraction.
8. Transport costs for the final product are negligible.
9. Diamond prices generally increase at a level which keeps pace or exceeds inflation.
10. The occasional large diamond (a 100 carat rough gem can be sold for about US\$1.7 million) found during production can be regarded as an added bonus.

Despite the above, the risks and costs of a diamond exploration programme can be very high, but the occasional reward can be even greater!

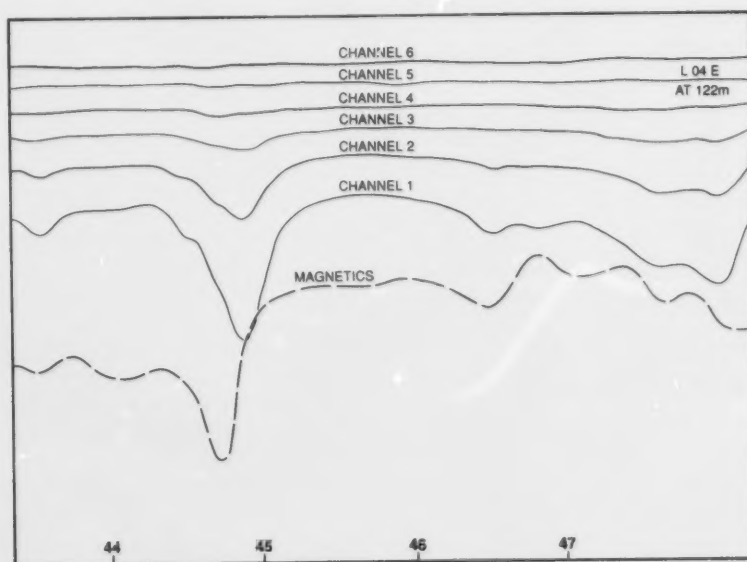


Figure 8 - INPUT and magnetic profile at 122 m above a kimberlite pipe.

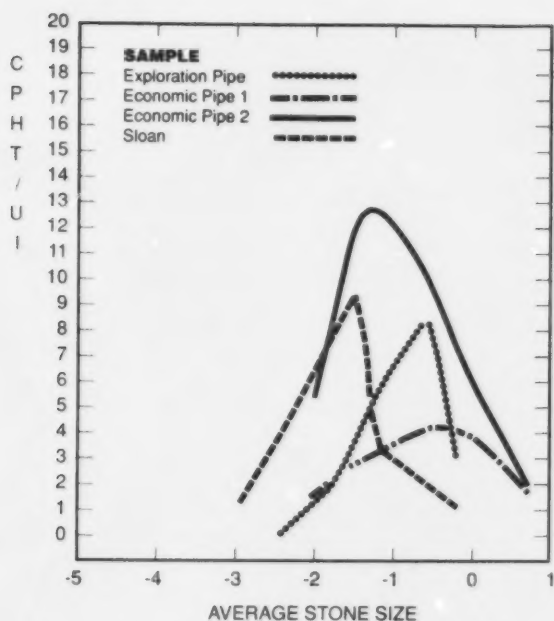


Figure 9 - Microdiamond distribution - carats per 100 tons versus size.

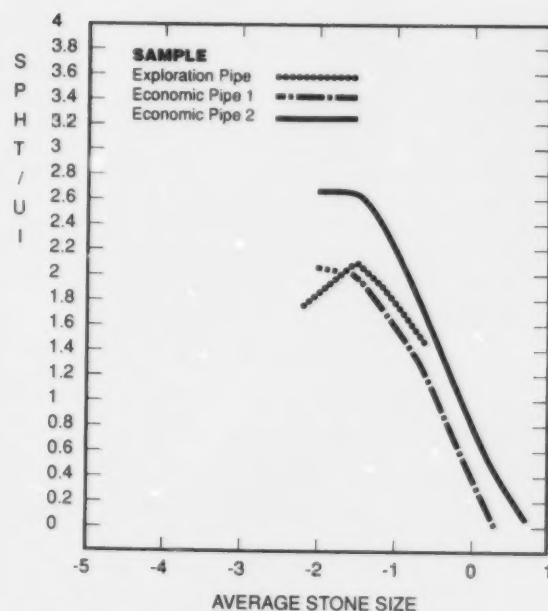


Figure 10 - Microdiamond distribution - number of stones versus size.

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THE USE OF AEROMAGNETICS AND VECTOR MAGNETICS IN GOLD AND DIAMOND SEARCH WITH EXAMPLES FROM BOTSWANA AND AUSTRALIA

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ABSTRACT

The Vector-Mag system is flown on a Cessna 206 Aircraft and measures the total magnetic field using three Scintrex H6 cesium vapour sensors, two mounted on the wingtips and a third installed as a conventional tail stinger enabling both transverse and longitudinal gradients to be measured. The magnetometer counting circuitry and aircraft acquisition system were developed at Aerodata Holdings Ltd., Australia. Separation between the wingtip sensors is 14.9 metres and the axial separation between the tail sensor and wingtip sensors is 6.9 metres. Compensation of aircraft manoeuvre noise was accomplished with in-house software to reduce noise levels by factors of 10-20.

Recently a PICODAS gradiometer acquisition system was installed in the aircraft. The system samples each sensor with a resolution of 10^{-3} nT and the compensation software reduces manoeuvre noise to less than 10pt/metre.

Gradiometer measurements offer a number of advantages over measurements of the total magnetic intensity. Superior resolution of closely spaced geological features and better definition and location of geological contacts are important advantages in exploration.

Very small variations in the total field data can be assigned to geological or other non-temporal sources if they are supported by corresponding variations in the gradients. This confidence is of vital importance in exploration for diamondiferous kimberlites and lamproites, and other targets such as precious and base metal ore bodies with minor associated pyrrhotite where the magnetic response of the target is subdued. Gradient data also enhances near surface features and discriminates against deeper features.

Horizontal gradient information can be incorporated into the imaging and contouring of total field data permitting a better portrayal of geological trends, overcoming the 'bullseye' and other mapping errors commonly created by anisotropic sampling of data.

Arrow maps where the total horizontal gradient vector is represented as an arrow, and contours of total horizontal gradient and total horizontal gradient processed with automatic gain control (AGC) have proved to be useful displays of gradient data. As with total magnetic intensity information the image processor offers decisive advantages for the display of magnetic gradient data. Judicious use of colour and shading enables a geologically meaningful presentation where subtle magnetic features are emphasized.

CRUSTAL EVOLUTION OF THE BURIED PRECAMBRIAN OF SOUTHERN SASKATCHEWAN: IMPLICATIONS FOR DIAMOND EXPLORATION

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ABSTRACT

Available data indicate that buried Precambrian basement in Saskatchewan largely comprises Archean crust, variably affected by Hudsonian thermotectonism during intercratonic collision that formed the Trans-Hudson Orogen. Assembly of crustal components in this segment of the orogen probably involved both thrusting and transcurrent movements which dismembered and obliterated juvenile arc terrains exposed at possible higher structural levels in northern Saskatchewan. Basement cores mainly comprise meta-igneous and metasedimentary rocks ranging in metamorphic grade from low amphibolite to granulite facies. Exceptions occur in the Choiceland area, where basement rocks are at low metamorphic grade, and the Swift Current area, where ca. 1760 Ma, post-tectonic, high-level granitoids cut Archean gneisses.

Sm-Nd crust formation ages for the basement cores range from ca. 3.3 to 2.3 Ga. The majority have ϵ_{Nd} ($t = 1870$ Ma) in the range -1.7 to -13.6. By contrast, juvenile Proterozoic rocks from the Trans-Hudson Orogen have ϵ_{Nd} ($t = 1870$ Ma) in the range +4.6 to -1.1. Only two samples with ϵ_{Nd} ($t = 1870$ Ma) of +3.5 and +0.6 clearly exhibit juvenile Early Proterozoic crustal signatures. Granitoids from the Swift Current Anorogenic Province with initial Nd isotopic compositions in the range ϵ_{Nd} ($t = 1760$ Ma) -1.3 to -6.7 are interpreted as melts of Archean crust.

Results show the utility of Sm-Nd isotopic data in providing first order geochronological constraints in areas where basement rocks are obscured by thick sequences of sedimentary cover. Knowledge of age, lithology and structure of the basement, and by inference the age of the subcontinental lithospheric mantle, has important implications for location and diamond potential of kimberlitic and other potassic igneous suites that occur in rocks in the region. Emplacement of these igneous bodies appears to be strongly controlled by basement linear elements and flexures that cut the northeasterly-trending Great Falls Tectonic Zone.

INTRODUCTION

The almost entirely unexposed 'Dakota segment' of the Trans-Hudson Orogen extends southward from the exposed Precambrian Shield, through southern Saskatchewan and Manitoba into Montana and the Dakotas. Better documentation of its age and character is critical for refinement of tectonic models of

Early Proterozoic assembly and thermotectonic evolution of the North American Craton (cf. Green *et al.*, 1985a, b; Hoffman, 1988; Lewry and Collerson, in press; Bickford *et al.*, 1990). Information regarding time of crust formation also has implications for the age of underlying lithospheric mantle. This in turn has a bearing on thermal history and thickness of mantle lithosphere and consequently, the economic

potential of intracratonic potassic igneous suites (e.g. kimberlites and lamproites), that are derived from, or that sampled, this heterogeneous region.

Previous petrological and geochemical studies of basement specimens recovered from drill-core in this region have been carried out by King (1966), Burwash and Culbert (1976), Burwash and Cumming (1974), Burwash and Krupicka (1969, 1970), Burwash *et al.* (1962, 1973), Rosholt *et al.* (1970), Peterman and Hedge (1964), Peterman and Goldich (1982), Frost and Burwash (1986), Peterman and Futa (1987), and Klasner and King (1986). Provisional whole rock Sm-Nd model ages and U-Pb zircon geochronological data for a reconnaissance suite of samples from the sub-Phanerozoic Saskatchewan basement were presented by Collerson *et al.* (1988a, 1989 a, b).

This paper includes further Sm-Nd age data for basement cores from southern Saskatchewan. Data are interpreted in the context of: 1) established lithotectonic elements in the exposed shield (Lewry, 1981, 1984; Lewry *et al.*, 1985; Lewry and Collerson, in press); 2) U-Pb zircon geochronology (Van Schmus *et al.*, 1987a); 3) Rb-Sr, Sm-Nd and Pb-Pb isotope systematics in the exposed shield (Chauvel *et al.*, 1987; Thom *et al.*, in press); and 4) geophysical data (Dutch, 1983; Arvidson *et al.*, 1984; Green *et al.*, 1985a, b; Klasner and King 1986). Results illustrate the utility of Sm-Nd model age data in providing first order geochronological constraints on the timing of crust formation in areas where variably reworked basement rocks are obscured by cover sequences.

If interpreted correctly (Arndt and Goldstein, 1987), model ages provide information on the time of separation of protoliths of the basement rocks from their mantle source region and on their subsequent crustal evolutionary histories. Our results complement studies of the basement of the Western Canadian Sedimentary Basin in Alberta and southern British Columbia (Frost and O'Nions, 1984; Ross *et al.*, 1988) and provide more complete understanding of the geological evolution of the concealed mid-continental region of the North American Craton (cf. Peterman, 1981; Nelson and DePaolo, 1985; Van Schmus *et al.*, 1987b; Sims and Peterman, 1986; Frost and Burwash, 1986; Peterman and Futa, 1987).

GEOLOGY OF THE EXPOSED SHIELD

U-Pb zircon geochronological studies in the Reindeer Zone or the eastern part of the exposed 'Thelon segment' of the Trans-Hudson Orogen in Saskatchewan (Van Schmus *et al.*, 1987a; Lewry *et al.*, 1987) suggest that lithotectonic belts southeast of the Wathaman Batholith formed largely by accretion of juvenile volcanic and plutonic arcs and by docking

of outboard terrains during a relatively short time interval, ca. 1830-1890 Ma. Reconnaissance Nd and Pb isotopic data for these juvenile terrains (Chauvel *et al.*, 1987; Thom *et al.*, in press) indicate that some of them incorporate an older (Archean) crustal component. Isotopic evidence of this component appears to increase systematically from the La Ronge magmatic arc northwestwards to the Wathaman Batholith. These isotope systematics are interpreted to reflect mixing between juvenile Proterozoic crust and variable amounts of Archean crust, thorough sedimentary and volcanoplutonic processes. In contrast, terrains west and northwest of the Wathaman Batholith consist predominantly of variably reworked Archean crust (Lewry *et al.*, 1985) and are considered to have possessed a relatively coherent cratonic platform during the period of late Early Proterozoic juvenile crust formation in the Reindeer Zone (Lewry *et al.*, 1985; Lewry and Collerson, in press; Bickford *et al.*, 1990).

The region lying between the Wathaman Batholith and the eastern boundary of the Slave Craton, including the 'Western Craton' or Amer Lake Zone of Lewry and Sibbald (1980) and Lewry *et al.*, (1985) and the Cree Lake Zone of Lewry *et al.*, (1985), has been subdivided by Hoffman (1988) into the Rae and Hearne provinces. These provinces are separated by an important transcontinental lineament or possible suture termed the Snowbird Tectonic Zone (Hoffman, 1988). The geotectonic status of the Snowbird Tectonic Zone is equivocal (Carolan *et al.*, 1989; Lewry and Collerson, in press); consequently, it is unclear whether the Rae and Hearne 'provinces' behaved as separate entities or constituted a single coherent continental plate during the Trans-Hudson Orogeny. Lewry and Collerson (in press) have proposed the term Rae-Hearne platform to encompass both the Rae and Hearne 'provinces'. This platform is dominated by Archean gneissic crust, which is partially covered by Early Proterozoic platform deposits.

Geological relations in La Ronge, Glennie, Kiseeynew and Flin Flon Domains of the Reindeer Zone have recently been interpreted as reflecting thin-skinned tectonic activity driven by crustal shortening during collisional orogeny, i.e. development and transport of complex allochthonous nappes and imbricated fold/thrust stacks. Chiarenzelli *et al.* (1987) and Lewry *et al.* (in press) have shown that windows of Archean gneisses (the Iskwtikan Complex and parts of the Nistowiak gneisses) are exposed at lower structural levels in the southwest part of the Glennie Domain. Such relationships suggest that much of the southeastern part of the Reindeer Zone may be possibly underlain by Late Archean crust, which has been overridden by allochthonous juvenile

Proterozoic crust subsequent to arc formation, during terminal collision within the orogen.

GEOLOGY OF THE BURIED BASEMENT

Basement cores investigated in this study are listed in Table 1 and located in Figure 1. The basement comprises a varied assemblage of meta-igneous and metasedimentary rocks representing components of the Superior and Wyoming-Rae-Hearne 'craton' as well as southerly extensions of the Early Proterozoic (ca. 1800-1900 Ma) Trans-Hudson Orogen (Hoffman, 1988; Bickford *et al.* 1990; Lewry and Collerson, in press). Lithological descriptions of basement core samples investigated in the current study are given in Collerson *et al.* (1988b, 1989a). Metamorphic grades range from lower amphibolite to granulite facies (Figure 2). In general, metamorphic domains appear to have a north-south elongation. Petrographic investigations were carried out to determine the extent to which groups of basement rocks could be correlated with lithotectonic elements in the exposed shield. However, exposed domains in the north are lithologically diverse and tectonically complicated (Lewry *et al.*, 1985; Lewry and Collerson, in

press) and, in view of the limited number of subsurface samples, correlations are difficult to establish. Nonetheless, several interesting features were identified. These are discussed below in terms of a broad geographic subdivision of the exposed and unexposed basement.

Northwestern Area

Cores from this area include orthopyroxene-hornblende-bearing quartzofeldspathic gneiss (SASK-35), granulite facies garnet-cordierite-sillimanite-K-feldspar-bearing pelitic gneiss (SASK-38), garnet-hornblende-bearing felsic gneiss (SASK-41), biotite-muscovite-microcline-bearing granitic gneiss (SASK-40) and augen granitic gneiss (SASK-32). The character of these rocks and their grade of metamorphism are consistent with much of the exposed Cree Lake Zone and with its extrapolation to the south and southwest (Figure 2).

Southwestern Area

Basement lithologies in this area include hornblende-bearing (amphibolite facies) mafic tonalitic gneiss (SASK-43), massive orthoquartzite (SASK-42), and

Table 1 - Location and Description of Basement Cores, Saskatchewan

Spec.No.	Location	Well Name	Lithology
SASK-1	16-04-03-32W1	Socony Western Carievale	Granitic gneiss
SASK-2	8-30-08-33W1	SMUS South Parkman	Tonalitic gneiss
SASK-4	10-25-36-05W2	Ceepee Annette	Blastomylonite
SASK-5	3-27-08-08W2	Imp. Can. Superior Stoughton	Bi-Musc-Cord gneiss
SASK-6	15-05-46-09W2	Calif. Std. Bannock	Alt. porph. microgranite
SASK-8	9-22-45-12W2	Peesane No.2 Stratigraphic test	Intermediate granulite
SASK-9	13-18-52-13W2	Triad Whitefox	Biotite-muscovite gneiss
SASK-10	12-15-52-14W2	Triad Whitefox	Gt-Cord-Bi-Sill gneiss
SASK-11	1-15-48-17W2	California Standard Ratner	Musc-Bi schist
SASK-15	8-09-50-18W2	Imperial <i>et al.</i> , Fort a La Corne	Phyllite
SASK-16	4-10-50-18W2	Irex A	Banded-iron formation
SASK-18	2-05-61-24W2	Gt. Plains Montreal Lake No. 25	Bi-Musc-Gt-Ct-sulphide schist
SASK-19	1-14-10-27-25W2	Tide Water Stalwart Crown No. 1	Altered granite
SASK-20	2-11-15-26W2	Ceepee Baildon	Mesoperthite-bi-granite
SASK-21	5-22-62-26W2	Great Plains <i>et al.</i> , Montreal Lk.	Altered tonalitic gneiss
SASK-22 ¹	4-16-37-01W3	White Roses <i>et al.</i> , St Denis	Granodioritic gneiss
SASK-22 ²			Dioritic gneiss
SASK-24	9-20-12-02W3	Johnston Lake Crown	Porphyritic microgranite
SASK-23	3-18-63-01W3	Gt. Plains McDermott Home Hay	Gt-Bi-Sill-Cord-gneiss
SASK-25	8-15-52-02W3	Mobil Oil von Mehren Lake X	Biotite-bearing tonalitic gneiss
SASK-26	8-08-64-02W3	Great Plains <i>et al.</i> , Musquash	Biotite-bearing tonalitic gneiss
SASK-27	1-36-63-05W3	Great Plains <i>et al.</i> , Smoothstone	Amph-biotite gneiss
SASK-29	1-09-17-14W3	B.A. Wilhelm	Amph-Bi micro-granite
SASK-30	3-10-17-14W3	B.A. Sask Lndg Wilhelm	Porph. micro-granite-rhyolite
SASK-32	8-30-64-15W3	Seaboard Meadow Lk. Crown No.3	Microcline-biotite gneiss
SASK-34	2-21-16-17W3	M.U.S. Cantuar	Bi-microcline granite
SASK-35	7-14-56-17W3	Canadian Seaboard Divide No.2	Charnokitic gneiss
SASK-36	2-04-10-19W3	Delhi <i>et al.</i> , Rock Cr2A	Granite
SASK-38	6-05-51-20W3	Husky D.H. Turtleford	Gt-Bi-Sill-Cord gneiss
SASK-39	9-32-06-22W3	M.O.W.S. Knollys	Albite granite
SASK-40	8-11-62-22W3	Imperial Goodsoil	Microcline-bi granitic gneiss
SASK-41	6-01-49-24W3	Husky D.L. Lashburn	Gt-Bi-Plag gneiss
SASK-42	4-31-03-26W3	Imperial <i>et al.</i> , Battle Creek	Diopside-bearing quartzite
SASK-43	1-31-18-28W3	Mobile Oil North Richmond	Dioritic gneiss
SASK-48	3-08-17-19W2	University of Regina	Megacrystic Gt-gr. gneiss
SASK-137	15-03-17-18W2	Fosterton W.S.15-3 °C	Hastingsite-bearing granite

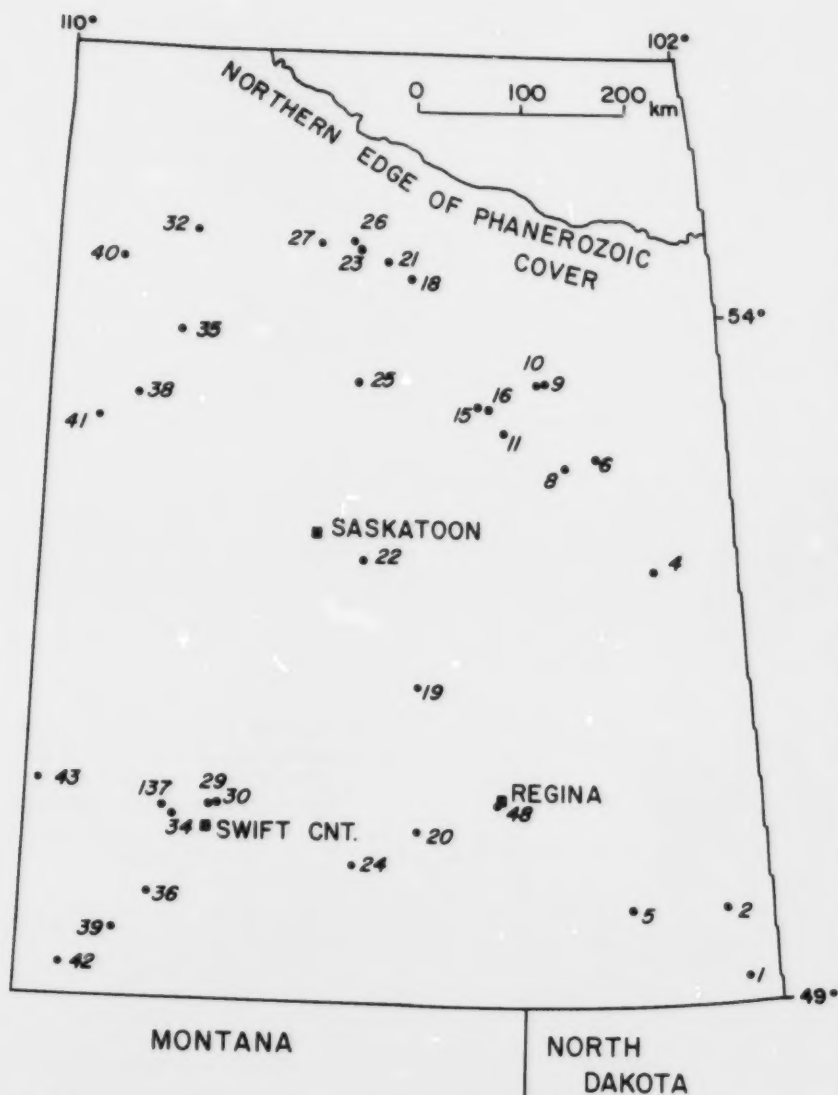


Figure 1 - Map of central and southern Saskatchewan showing the geographic distribution of basement cores examined in this study. The numbers are the sample numbers.

varied undeformed granites (SASK-39, -36, -34, -137, -24) and felsic volcanics or high-level porphyry intrusions (SASK-24, -29, -30).

Metamorphic grade of the quartzite is equivocal, although, the presence of traces of diopside and the nature of recrystallized microstructures suggests amphibolite facies conditions of metamorphism. The quartzite yields a Nd crustal residence age of 2840 Ma (Frost and Burwash, 1986); however, this may be a provenance age and the unit may represent an Early Proterozoic shelf sequence, comparable with either the Snowy Pass Supergroup of the Medicine

Bow Mountains in southeast Wyoming, or possibly parts of the Wollaston Group.

Significant, and unexpected, lithologies in the southwest include post-tectonic rapikivi granites containing large compositionally zoned K-feldspar megacrysts, and porphyritic rhyolites, considered to be high-level intrusives or extrusives. Ferrohastingsite occurs in both the granitoids and the rhyolites. Previously published U-Th-Pb geochronological data for a granite from this suite indicated a crystallization age of ca. 1790 Ma (Rosholt *et al.*, 1970). The same sample analyzed in this study has yielded a U-Pb zircon discordia age of 1763 ± 4 Ma (Collerson *et al.*, in prep.). Neodymium isotopic data for two of these granites (SASK-36, -39) reported by Frost and Burwash (1986) give late Archean crust formation ages (2583 and 2621 Ma respectively). These data indicate that the granites represent melts of Archean crust. The suite is tentatively correlated with post-Hudsonian anorogenic magmatism of the Dubawnt Group in the Thelon Segment of the Trans-Hudson Orogen (Donaldson, 1965; Blake, 1980) and provides an important constraint on timing of tectonothermal activity in this part of the orogen. Specimen distribution suggests that a major area of anorogenic plutonic and volcanic activity extends from Swift Current south towards Montana. This region, termed the Swift Current Anorogenic Province (Figure 2), straddles the northeasterly extension of the Great Falls Tectonic Zone (O'Neill and Lopez, 1985) which has been the locus of igneous activity and recurrent fault movement from Early or Mid-Proterozoic time through to the Holocene. The Swift Current Anorogenic Province also extends

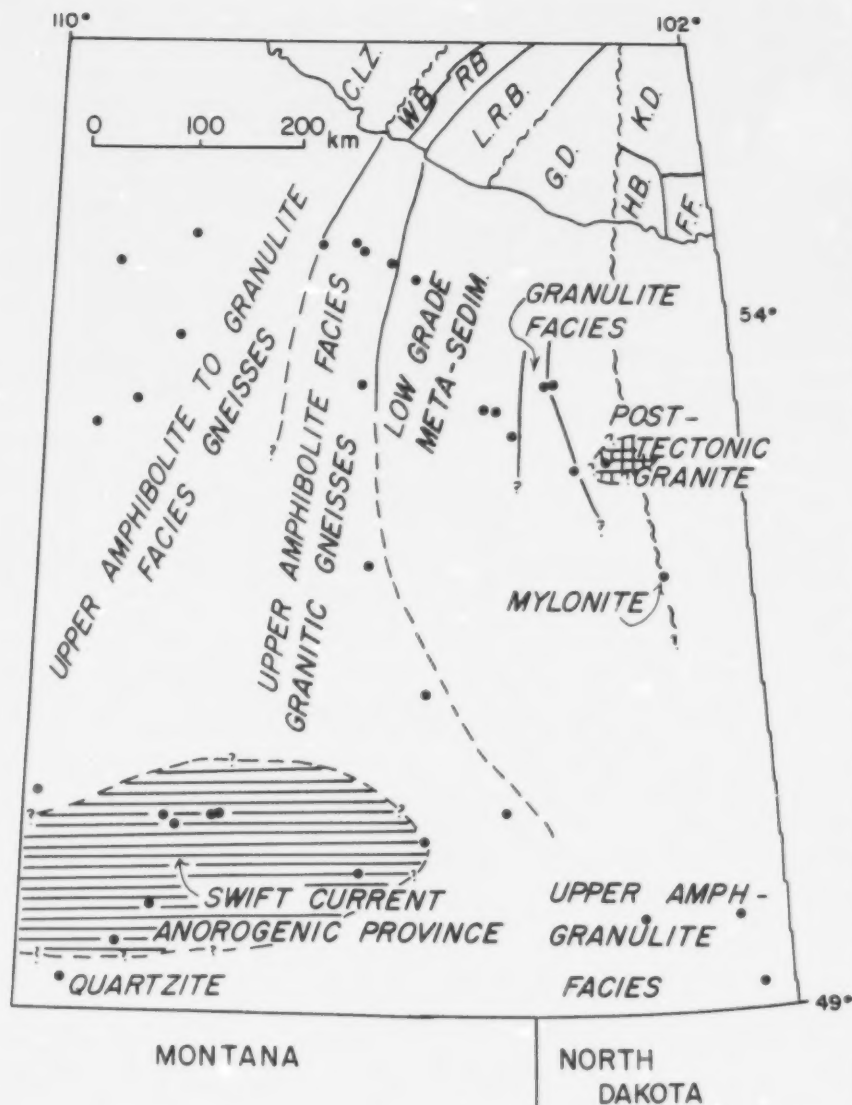


Figure 2 - Map showing variation in metamorphic grade and lithology in the sub-Phanerozoic basement cores from Saskatchewan. CLZ = Cree Lake Zone; WB = Wathaman Batholith; RB = Rottenstone Belt; LRB = LaRonge Belt (Domain); HB = Hanson Lake Block; KD = Kisseynew Domain; FF = Flin Flon Domain.

across the postulated northeastern margin of the Archean Wyoming Craton.

South-central Area

Cores from the Regina-Moose Jaw area (SASK-19, -20, -48) comprise weakly-to-moderately foliated, locally garnetiferous megacrystic and non-megacrystic granites similar to rocks of the Wathaman Batholith. Farther east, the basement is characterized by tonalitic and granodioritic gneisses (SASK-27),

medium- to high-grade migmatitic supracrustal rocks (SASK-18, -21, -22, -23, -25, -26) and varied, non-diagnostic pink granite and granodiorite. This marked change in lithological assemblage, similar to that occurring east of the exposed Wathaman Batholith, roughly coincides with the estimated position of the North American Central Plains Conductivity Anomaly (Camfield and Gough, 1977).

Southeastern Area

Basement cores in the southeast include upper amphibolite to granulite facies granitic and tonalitic orthogneisses (SASK-1, -2), and cordierite-bearing gneiss (SASK-5) believed to be derived from a supracrustal protolith. There is no evident correlation between lithology and postulated geophysical domain boundaries (Green *et al.*, 1985a,b). Two cores from North Dakota, close to the Saskatchewan border, contain zircons which yield U-Pb discordia intercept ages of *ca.* 2900 Ma, with lower intercepts of *ca.* 1650-1750 Ma (Peterman and Goldich, 1982). The cordierite gneiss (SASK-5) from Imperial Stoughton 3-27 gives a Sr model age of *ca.* 2500 Ma (Peterman and Hedge, 1964).

North-central and Northeastern Area

In the north-central/northeastern part of the unexposed shield, basement cores comprise granulite facies ortho- and paragneisses (SASK-8, -9, -10), and an altered granite rich in accessory minerals (SASK-6). These rocks lie west of a blastomylonitic zone (SASK-4), tentatively related to the Trans-Hudson Orogen-Superior boundary zone, and also west

of the geophysically extrapolated subsurface extension of the Tabernor Fault zone. One extremely fresh intermediate granulite (SASK-8) has yielded abundant, virtually concordant zircon (see below). These high-grade rocks lie south of low-grade areas in the exposed Glennie Domain and their significance is currently unclear.

In the Choiceland area, west of this high-grade terrain, metamorphic grade abruptly changes. Several boreholes (SASK-11, -15, -16) intersect a low-grade metasedimentary assemblage that contains thick sequences of banded-iron formation.

Sm-Nd Isotopic Data

Sm-Nd separation chemistry was carried out at the University of California, Santa Cruz using the following procedures. Samples weighing 70-100 mg were spiked with a mixed $^{149}\text{Sm}/^{150}\text{Nd}$ tracer prior to digestion to ensure spike equilibration. Following an initial open beaker evaporation, they were further decomposed with HF in teflon bombs for several days at a temperature of ca. 205°C. After removal from the oven, HClO_4 was added and the HF- HClO_4 mixture evaporated to dryness. Remaining insoluble fluorides were digested by treating the samples with 6N HCl in teflon capsules. The 6N HCl solution was partially evaporated and then diluted to ca. 1.0N, the concentration required for ion exchange chemistry. These bomb procedures were adopted to ensure total dissolution of such refractory REE-bearing phases as zircon and monazite.

Isotope ratios were measured on a seven collector VG 354 Sector thermal ionization mass spectrometer at UCSC using dynamic multi-collection techniques. Total processing blanks for Nd and Sm were between 40 and 30 pg per dissolution. Duplicate analyses with these digestion techniques agree within analytical uncertainty for both $^{147}\text{Sm}/^{144}\text{Nd}$ and $^{143}\text{Nd}/^{144}\text{Nd}$. Fractionation of isotope ratios was corrected using $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. The mean $^{143}\text{Nd}/^{144}\text{Nd}$ value obtained for 18 analyses of different loads of La Jolla Nd was 0.511853 with a relative standard deviation of 6 ppm at the 1 σ level. The decay constant for ^{147}Sm is $6.54 \times 10^{-12} \text{ a}^{-1}$. Model ages were calculated with respect to a depleted mantle with $\epsilon_{\text{Nd}}(t = 4.6 \text{ Ga})$ of 0 and $\epsilon_{\text{Nd}}(t = 0)$ of +10 (Goldstein *et al.*, 1984). Parameters used in the calculation of ϵ_{Nd} values were taken from Jacobsen and Wasserburg (1980).

Sm-Nd isotopic data are reported for 22 basement core samples distributed along three east-west traverses. Data presented in Collerson *et al.*, (1988a) were reanalyzed, and data for additional samples have been obtained. Results are given in Table 2 and summarized in Figures 3 and 4. Present-day ϵ_{Nd} values

reflect fractional deviation (expressed as parts in 10^4) of the present-day measured $^{143}\text{Nd}/^{144}\text{Nd}$ ratio from the present-day chondritic value (CHUR-DePaolo and Wasserburg, 1976). For samples with strongly fractionated REE patterns these ϵ_{Nd} values provide a good estimate of the antiquity of each rock (cf. DePaolo and Wasserburg, 1979). Most samples have $\epsilon_{\text{Nd}}(0)$ values in the range -19.6 and -34.4, and most have ϵ_{Nd} greater than -23 (Table 2). Such ratios are typical of late Archean suites (*ibid*). Two samples SASK-4 and -21 have significantly lower ϵ_{Nd} values. In the case of SASK-4, a blastomylonite, the low ϵ_{Nd} reflects a higher $^{147}\text{Sm}/^{144}\text{Nd}$ ratio and therefore greater production of radiogenic ^{143}Nd . This may indicate the presence of a mafic component in the mylonite; alternatively, it may reflect open-system behaviour that caused a loss of Nd during shearing and recrystallization. Duplicate digestions and analyses have been carried out on SASK-21, the other sample with a low ϵ_{Nd} . This rock is extremely altered, and the isotopic systematics have clearly been disturbed. To evaluate initial deviations from CHUR at 1870 Ma (Van Schmus *et al.*, 1987a; Bickford *et al.*, 1990), the approximate time of formation of the Trans-Hudson Orogen, $\epsilon_{\text{Nd}}(1870 \text{ Ma})$ values have been calculated. Most basement samples have $\epsilon_{\text{Nd}}(1870 \text{ Ma})$ in the range -2.0 to -13.6. Such negative ϵ_{Nd} values for the basement gneisses at this time clearly reflect involvement of Archean crust.

Nd isotopic data from the exposed shield in Saskatchewan (Chauvel *et al.*, 1987; Collerson, unpublished data) are compared with data from the buried basement in Figure 5. Juvenile Proterozoic rocks in the Trans-Hudson Orogen exhibit generally positive $\epsilon_{\text{Nd}}(1870 \text{ Ma})$ values of +4.6 to -1.0, which are interpreted as indicating involvement of melts derived from depleted mantle sources with high Sm/Nd ratios (Chauvel *et al.*, 1987). Present-day ϵ_{Nd} values for juvenile Proterozoic rocks from the La Ronge Belt (with broadly similar Sm/Nd ratios) range from -15.6 to -23.3. Suites that have similar present-day ϵ_{Nd} values to the basement data are the Sahli Granite in the Hanson Lake Block, and gneisses from the Rottenstone Domain, Wathaman Batholith, Peter Lake Domain, Cree Lake Zone and Western Granulite Domain. These suites all have Archean protoliths, or are interpreted to have sources containing mixed Archean and Early Proterozoic components. The only basement samples that may contain a component of juvenile Early Proterozoic material are SASK-11, a biotite-muscovite schist with $\epsilon_{\text{Nd}}(1870 \text{ Ma})$ of +0.6, that lies south of the Glennie Domain (Collerson *et al.*, 1988a), and SASK-4, the blastomylonite from the extrapolation of the Tabernor Fault with $\epsilon_{\text{Nd}}(1870 \text{ Ma})$ of +3.5.

Table 2 - Sm-Nd Isotopic Data for Basement Cores, Saskatchewan

Spec. No.	Sm (ppm)	Nd (ppm)	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd	ε _{Nd} (0)	T _{CR} (Ma)
SASK-4	2.76	10.32	0.1619	0.512389±34	-4.86	2246±98
SASK-5 ¹	12.11	63.61	0.1150	0.511270±5	-26.69	2892±8
SASK-5 ²	31.91	169.42	0.1138	0.511246±7	-27.15	2893±10
SASK-6	7.59	41.38	0.1109	0.511441±21	-23.35	2528±30
SASK-8	6.57	32.82	0.1209	0.511388±4	-24.38	2883±7
SASK-10	4.41	24.43	0.1092	0.511053±12	-30.92	3044±18
SASK-11	7.49	40.27	0.1125	0.511632±4	-19.62	2285±6
SASK-20	2.22	14.49	0.0925	0.511255±5	-26.98	2379±6
SASK-21	1.79	5.19	0.2091	0.512225±15	-8.06	—
SASK-21R	1.76	5.15	0.2064	0.512214±20	-8.27	—
SASK-22 ¹	7.13	50.22	0.0864	0.510900±32	-33.90	2684±37
SASK-22 ²	6.54	43.15	0.0916	0.511036±18	-31.25	2631±23
SASK-24	20.29	112.76	0.1088	0.511552±5	-21.18	2319±7
SASK-25	5.46	35.36	0.0933	0.511001±17	-31.93	2711±21
SASK-26	3.25	18.80	0.1047	0.511418±13	-23.80	2418±18
SASK-34	12.45	67.79	0.1110	0.511301±7	-26.08	2735±19
SASK-35	20.57	133.34	0.0932	0.510933±9	-33.26	2793±11
SASK-35R		136.29		0.510932±3	-33.28	
SASK-36*	4.07	26.64	0.1135	0.511448±24	-23.21	2583±36
SASK-38	5.97	33.30	0.1083	0.511074±9	-30.52	2988±13
SASK-39*	8.70	59.02	0.0891	0.511001±18	-31.93	2621±22
SASK-40	4.08	28.30	0.0870	0.510904±7	-33.83	2692±8
SASK-41	10.14	62.91	0.0974	0.510951±4	-32.91	
SASK-42*	0.77	4.13	0.1133	0.511275±26	-26.59	2836±39
SASK-43 ¹	1.73	9.59	0.1101	0.510877±30	-34.35	3323±43
SASK-43 ²	2.93	14.31	0.1239	0.511258±17	-26.92	3194±28
SASK-48	8.00	43.77	0.1104	0.511436±7	-23.45	2524±11
SASK-48R		43.79		0.511453±16	-23.12	

Uncertainties reported for each ratio are 2σ (mean).

Specimen numbers followed by 'R' represent duplicate digestions and analyses.

Data from Frost and O'Nions (1984) are shown by an *.

Specimen numbers designated /1 and /2 represent analyses of different lithological components in the core.

Uncertainties in the crustal residence ages were calculated using the precision for determination of each ¹⁴³Nd/¹⁴⁴Nd ratio.

Granitoids from the Swift Current Anorogenic Province have initial Nd isotopic compositions in the range ε_{Nd} (1760 Ma) of -1.3 to -7.7 and are interpreted as melts of Archean crust. The ε_{Nd} (1760 Ma) values provide maximum estimates of the isotopic composition of the sources at 1760 Ma, as melting and fractional crystallization both result in a decrease in the Sm/Nd of melts relative to their sources.

Crust formation ages for the basement cores range from ca. 2.3 to 3.3 Ga (Figure 4). These data contrast with U-Pb zircon ages of ca. 1.7 to 1.9 Ga for a number of these rocks (Collerson *et al.*, in prep). Nd model ages are interpreted as providing an estimate of the time elapsed since the rock had the same ¹⁴³Nd/¹⁴⁴Nd ratio as its mantle source region. Alternatively, if a rock represents mixtures of components derived from different crustal reservoirs of contrasting age, then the model ages will give an estimate of the average time that components of the rock have been in the crust (Arndt and Goldstein, 1987). Model ages for basement samples, ranging from

ca. 3.3 Ga to 2.3 Ga indicate that the sub-Phanerozoic extension of the Trans-Hudson Orogen is apparently not dominated by ca. 1870 to 1890 Ma juvenile crust, as suggested by Green *et al.*, (1985a, b) and Patchett and Arndt (1986). Rather, it is composed of older crust, albeit variably reworked by Hudsonian thermotectonism. This crustal reworking produced metamorphic zircon, and crystallization of magmatic zircon in penecontemporaneous crustal melts derived from source regions that contained large volumes of earlier crust. Protoliths of this crust probably separated from the mantle during the late Archean and possibly the very early Proterozoic. Somewhat lower model ages exhibited by granitoids in the Swift Current Anorogenic Province (ca. 2.3 to 2.7 Ga), reflect the effect of fractionation of Nd and Sm during partial melting. As this process caused an increase in Nd/Sm (Wilson *et al.*, 1985) the model ages are minimum estimates of the age of the granite source region which is presumably the northern extension of the Archean Wyoming Craton.

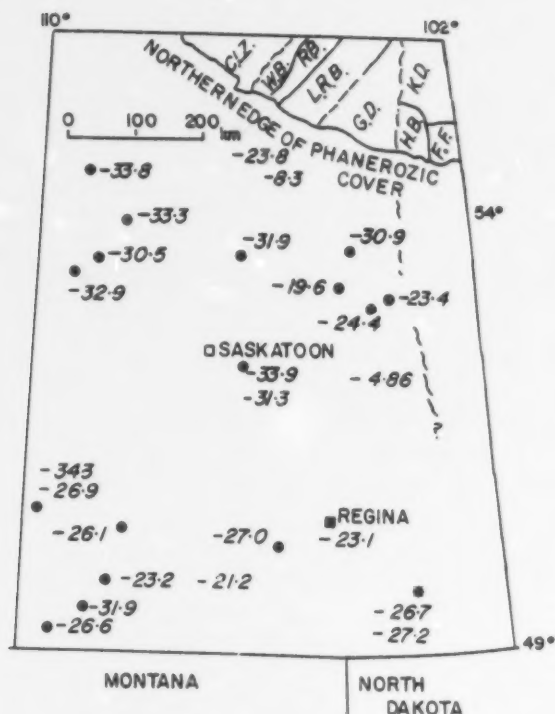


Figure 3 - $\epsilon_{Nd}(0)$ values for basement samples. These data give the fractional deviation expressed as parts in 10^4 of the measured $^{143}\text{Nd}/^{144}\text{Nd}$ ratio from the present day value of CHUR (DePaolo and Wasserburg, 1976). (For abbreviations see Figure 2).

DISCUSSION

Sm-Nd isotopic data from Precambrian basement terrains allow broad constraints to be placed on time of separation of continental crustal components from their mantle source regions (e.g. DePaolo and Wasserburg, 1976; McCulloch and Wasserburg, 1978; Allegre and Ben Othman, 1980; DePaolo, 1981; McCulloch and Compston, 1981; Collerson and McCulloch, 1982; Patchett and Bridgwater, 1984; Wilson *et al.*, 1985; Patchett and Kouvo, 1986; Chauvel *et al.*, 1987). In Early Proterozoic orogenic belts, such studies have allowed distinctions to be made between reworked Archean crust, and crust formed by accretion of juvenile (short-lived mantle-derived) magmatic arcs (Patchett and Bridgwater, 1984; Patchett and Kouvo, 1986).

As discussed above, Nd model ages give an estimate of the time that has elapsed since a crustal rock had the same $^{143}\text{Nd}/^{144}\text{Nd}$ ratio as its mantle source region. The approach assumes that there was only a short time interval between fractionation of Sm/Nd during partial melting and addition of the material to the continental crust. Model ages are only valid if assumptions concerning the source from which the crustal melts are derived are correct (Arndt and

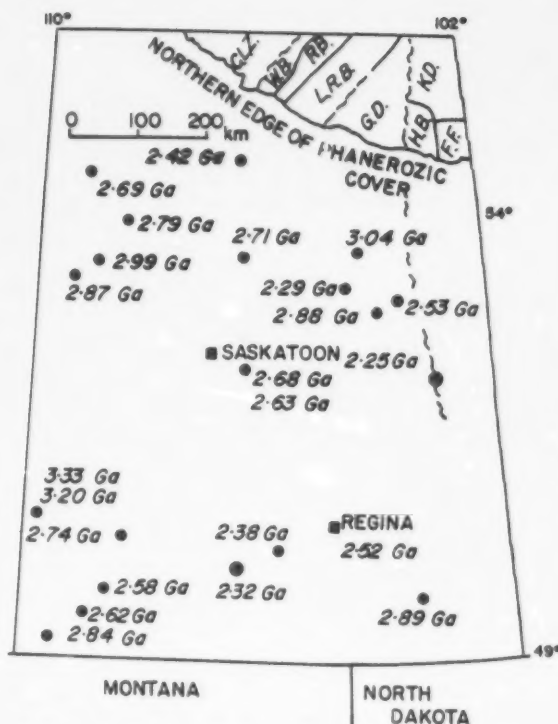


Figure 4 - Sm-Nd crustal residence model ages for basement samples. These ages are calculated assuming that the crust has separated from a depleted mantle source. (For abbreviations see Figure 2).

Goldstein, 1987). Figure 6 gives a graphical representation of the method employed to calculate different types of model ages. Initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios obtained for mantle-derived Archean and Proterozoic suites indicate derivation from light rare earth depleted mantle (DM) source regions with Sm/Nd ratios greater than that of a mantle reservoir with a chondritic Sm/Nd ratio (CHUR). Model ages that assume derivation from such a source region are considered as crustal residence ages (TCR). Although there is debate concerning the origin of the depleted mantle reservoir, the increase in Sm/Nd in the mantle is considered to be the result of depletion in Nd, due to removal of a light rare earth enriched component (DePaolo, 1981; Chase and Patchett, 1988; Smith and Ludden, 1989; Collerson *et al.*, 1990a). This enriched component is widely believed to be the continental crust (McCulloch and Compston, 1981).

Although it has generally been considered that the Sm-Nd isotopic system is little affected by crustal processes, some fractionation of Sm/Nd ratio may occur under both metamorphic and anatexis conditions on both a mineralogical and whole-rock scale (e.g. McCulloch and Black, 1984; Wilson *et al.*, 1985; Collerson *et al.*, 1989c). As a result, Sm-Nd model

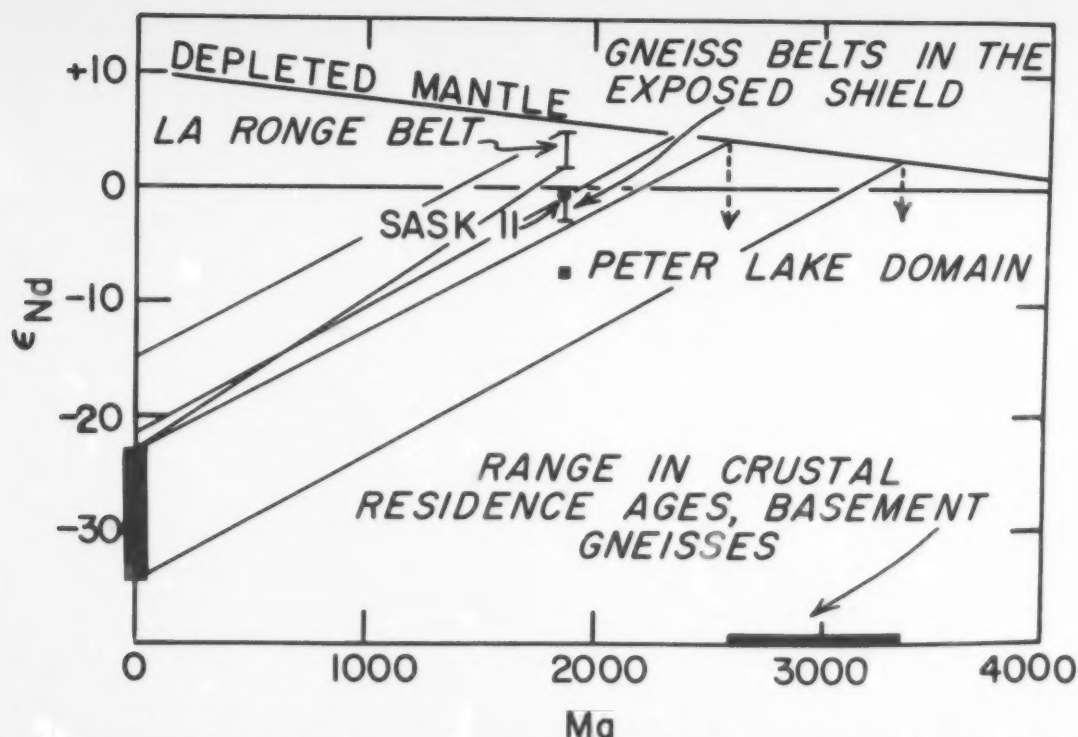


Figure 5 - $\epsilon_{Nd}(0)$ versus time diagram showing comparison between the Nd isotope systematics of juvenile Proterozoic rocks from the La Ronge Belt, gneisses from the Rottenstone Belt and Peter Lake Domain gneisses (Chauvel et al., 1987) and data for samples from the buried basement. Juvenile Proterozoic rocks in the Trans-Hudson Orogen exhibit generally positive ϵ_{Nd} (1870 Ma) values which are interpreted to indicate involvement of melts derived from depleted mantle sources. The more negative character of ϵ_{Nd} for gneisses from the Trans-Hudson Orogen (shown by the solid vertical ornamentation) reflects the involvement of some Archean crust in the genesis of these gneiss belts. Even more negative ϵ_{Nd} data for the basement cores contrasts with data from the exposed shield and clearly shows their greater antiquity.

ages may yield equivocal information about the time of crust generation and thus, of crustal residence. The effect of isotopic homogenization due to redistribution of Nd and/or Sm during metamorphism will depend to a large degree on the scale of diffusion in relation to the scale of sample volume. The closed system evolution of two co-magmatic rocks (WR1 and WR2) with different Sm/Nd ratios between the time of crust formation from a depleted mantle source ca. 3400 Ma ago and a period of metamorphism ca. 2700 Ma ago is shown in Figure 7. Both rocks evolve to negative ϵ_{Nd} values at TMETA, because their Sm/Nd ratios are less than that of the chondritic reservoir (CHUR). During metamorphism, re-equilibration causes a decrease in the ϵ_{Nd} of WR2 and an increase in the ϵ_{Nd} of WR1 as a result of isotopic exchange. At the termination of the metamorphic event, the isochron is essentially re-set to a zero slope, with a new initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratio controlled by the average ϵ_{Nd} of WR1 and WR2. The slope of the secondary isochron gives the age of TMETA. In this analysis, the value of ϵ_{Nd} (TMETA) is a minimum value, when the Sm/Nd ratios of the whole rock samples are less than CHUR. Samples

with ϵ_{Nd} values < 0 , like those exhibited by the basement data, usually represent rocks with a significant crustal prehistory.

Currently available Sm-Nd isotopic data indicate the following:

- 1) Buried basement in south and central Saskatchewan contains a significant Archean (Wyoming-Hearne-Rae 'platform') crustal component that was variably affected by Hudsonian thermotectonism associated with intercratonic collision. Hudsonian U-Pb zircon ages reflect growth of metamorphic zircon and crystallization of zircon in penecontemporaneous crustal melts derived from Archean crust.
- 2) Superior Craton Archean crust occurs further west than has been previously thought on the basis of geophysical data (cf. Green et al., 1985a, b).

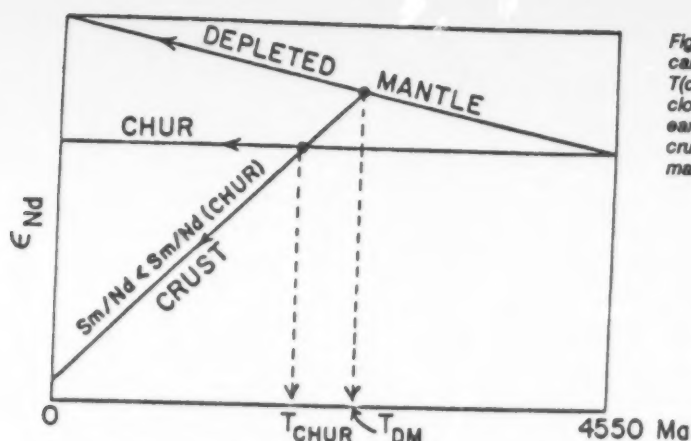


Figure 6 - $\epsilon_{Nd}(0)$ versus time diagram showing graphically the meaning of Nd model $T(CHUR)$ and $T(DM)$ or $T(\text{crustal residence})$ ages. These calculations assume closed system evolution, following a melting/rare earth fractionation event that produced a hypothetical crustal reservoir with a lower Sm/Nd ratio than its mantle source (CHUR or DM).

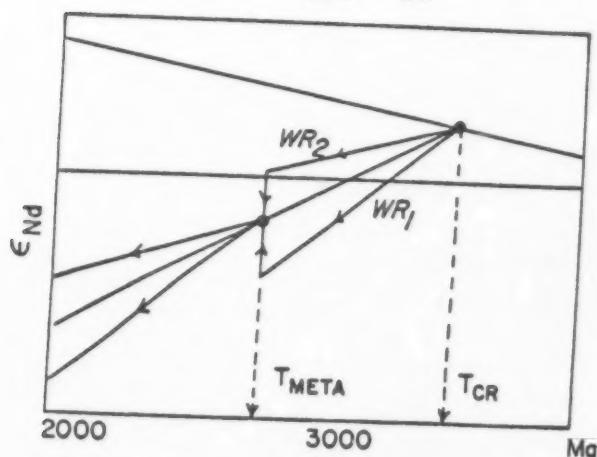


Figure 7 - $\epsilon_{Nd}(0)$ versus time diagram showing possible effect of later metamorphism on Nd isotope systematics. of two co-magmatic rocks (WR1 and WR2) with different Sm/Nd ratios between the time of crust formation from a depleted mantle source ca. 3400 Ma ago and a period of metamorphism ca. 2700 Ma ago. Both rocks evolve to negative ϵ_{Nd} values at T_{META} , because their Sm/Nd ratios are less than that of the chondritic reservoir (CHUR). During metamorphism, re-equilibration causes a decrease in the ϵ_{Nd} of WR2 and an increase in the ϵ_{Nd} of WR1 as a result of isotopic exchange. At this time an isochron for these rocks would have a zero slope and a new initial $^{143}Nd/^{144}Nd$ ratio. $\epsilon_{Nd}(T_{META})$ is a minimum value, when the Sm/Nd ratio of the whole rock samples is less than CHUR.

- 3) The Swift Current Anorogenic Province formed by partial melting of Archean crust during a late Hudsonian or post Hudsonian event ca. 1760 Ma ago.
- 4) Late Hudsonian evolution in the Dakota segment of the Trans-Hudson Orogen probably involved crustal thickening and transcurrent movement, during which the arc terrains exposed in the north were dismembered and obliterated (cf. Green *et al.*, 1985a, b).

The data provide no evidence for the presence of juvenile Early Proterozoic crust similar to that exposed in northern Saskatchewan (Lewry *et al.*, 1989; Bickford *et al.*, 1990). Consequently, the estimate by Patchett and Arndt (1986) of the volume of juvenile crust in the Reindeer Zone formed during the Trans-Hudson Orogen (ca. 92%) is probably too large.

IMPLICATIONS FOR DIAMOND EXPLORATION

The widespread occurrence of Archean crust in the buried basement of southern Saskatchewan imposes significant constraints on tectonic models for evolution of the Trans-Hudson Orogen and on geophysically based extrapolations of lithotectonic elements within the buried basement. Occurrence of crust of this age implies that the region is probably underlain by thick, relatively cool and very ancient lithospheric mantle of similar composition to that represented by mantle xenoliths from Montana. Suites of these xenoliths and host Cenozoic lavas have recently been documented by Dudas *et al.* (1987), Hearn *et al.* (1989), Irving *et al.* (1989), and Collerson *et al.* (1990b). Isotopic data for these suites indicate the presence of extremely heterogeneous enriched mantle sources beneath Montana (Figure 8). Nd model age data show that this geochemical enrichment occurred during the mid to early Proterozoic, possibly during formation of the Trans-Hudson Orogen (Collerson *et al.*, 1990b). Petrographic data for high-pressure granulite facies xenoliths in minet-

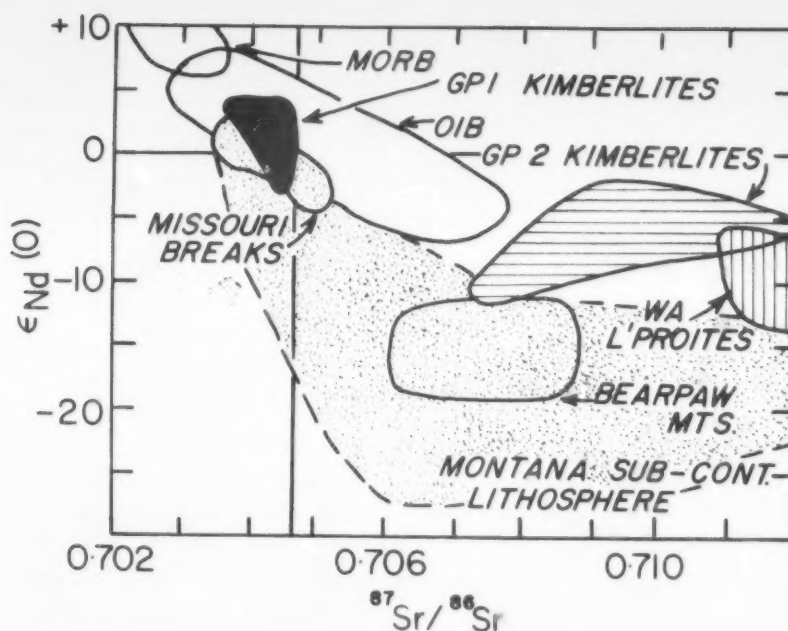


Figure 8 - Diagram showing covariation between $\epsilon_{Nd}(0)$ and $^{87}Sr/^{86}Sr$ in igneous rocks derived from the sub-continental lithospheric and asthenospheric mantle below the Wyoming Craton (light stipple). The mantle below Wyoming craton is clearly ancient and very heterogeneous in terms of Rb/Sr and Sm/Nd. Shown for comparison are data for mid-ocean ridge basalts (MORB's), ocean island basalts (OIB's), Group 1 basaltic kimberlites, Group 2 micaceous kimberlites and lamproites from Western Australia. Data are from McCulloch *et al.* (1983); Irving *et al.* (1989); Smith (1983); Collerson *et al.* (1990b); Dudas *et al.* (1987); Vollmer *et al.* (1984).

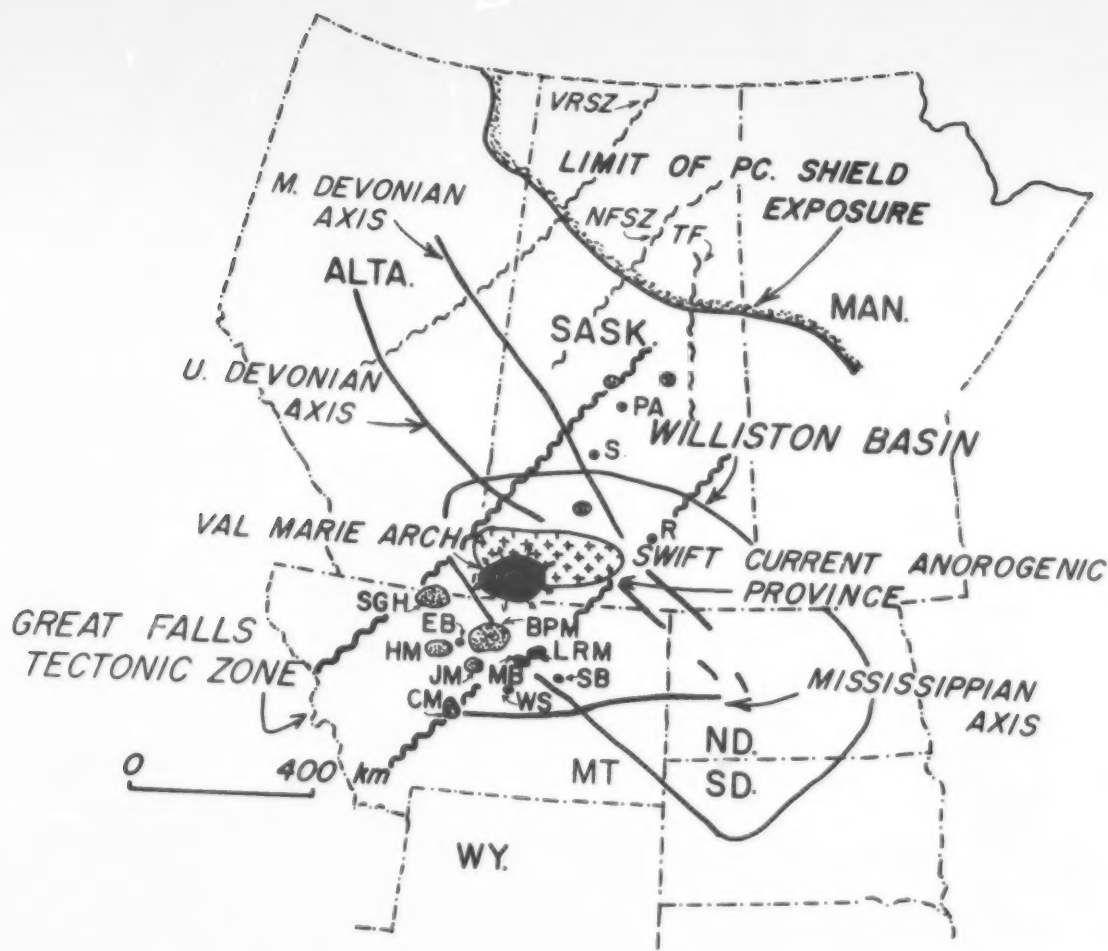
tes from the Bearpaw Mountains (Collerson *et al.*, 1988b; Collerson *et al.*, 1989d; Collerson *et al.*, 1990b) have shown that crust in this part of the Wyoming Craton is ca. 45-50 km thick, similar to geophysically established estimates of crustal thickness beneath buried rocks of the Trans-Hudson Orogen in the Williston Basin (Morel-à-l'Hussier *et al.*, 1987).

Tertiary igneous rocks form a major volcanic and plutonic alkaline province in north-central Montana (Marvin *et al.*, 1980; Hearn, 1989). One of the largest of these centers occurs in the Bearpaw Mountains (Figure 9). In this area, Cretaceous, Jurassic and Mississippian sedimentary rocks overlying Archean basement of the Wyoming Craton form an elongate anticlinal arch that was tectonically active during Phanerozoic sedimentation, volcanism and plutonism. Structures such as these, that were reactivated during crustal uplift, were clearly important in controlling emplacement of intracratonic potassic igneous suites in Montana and southern Alberta. Reactivated Archean and Early Proterozoic basement structures have also been shown by Kent (1987) to have played a significant role in controlling Phanerozoic depositional environments in parts of the Western Canadian sedimentary basin; for example, in areas of the basin underlain by the Swift Current Platform and in a zone of presumed epirogenic crustal flexuring that lies adjacent to the axis of the maximum thickness of middle Devonian sedimentation in the Prince Albert area (Figure 9).

By analogy with other cratons (cf. Mitchell, 1986), and in view of the implied Archean age, as well as the significant thickness and stability of mantle lithosphere underlying the Precambrian basement in southern Saskatchewan, kimberlites in this region are potentially of economic significance. In view of the presently limited data on the distribution of kimberlites in Saskatchewan, no definitive statements can yet be made concerning possible basement structural control on their localization. However, there is some indication that their distribution pattern might be broadly related to a northeasterly extension of the Great Falls Tectonic Zone into Saskatchewan (Figure 9). It is possible that kimberlite emplacement might also be significantly localized by basement structural features similar to those identified by Kent (1987).

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OCCURRENCES OF POTASSIC SUITES

Figure 9 - Map showing location of potassic igneous suites in Montana, Alberta and Saskatchewan in relation to major basement structural features. Data for Montana are from Marvin et al. (1980) and Collerson et al. (1990b). Shown are the axes of maximum Mississippian and Devonian sedimentation, the Val Marie structural arch (solid oval; Kent, 1987), the trend of the Great Falls Tectonic Zone (O'Neill and Lopez, 1985), the Virgin River Shear Zone (VRSZ) - Snowbird Tectonic Zone, Needle Falls Shear Zone (NFSZ), and Tabbemor Fault (TF) from Lewry and Collerson (in press). Rocks of the Swift Current Anorogenic Province are shown by plus signs. SGH = Sweet Grass Hills; HM = Highwood Mountains; EB = Eagle Buttes; CM = Crazy Mountains; JM = Judith Mountains; BPM = Bearpaw Mountains; WS = Winnett Sill; MB = Missouri Breaks Diatremes; LRM = Little Rocky Mountains; SB = Smoky Butte; R = Regina; S = Saskatoon; PA = Prince Albert. The stippled ornament NE and NW of PA represent diatremes in the Fort a la Crosse and Sturgeon Lake areas respectively.

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ACKNOWLEDGEMENTS

We are grateful to Saskatchewan Energy and Mines for financial support through the Canada-Saskatchewan Mineral Development Agreement 1984-1989, when the senior author was a faculty member at the University of Regina, and to D.F. Paterson for assistance locating samples housed in the Subsurface Laboratory in Regina. This research was also supported by National Science Foundation Grants (EAR 87-20442) to Collerson, (EAR 87-19997) to Bickford and (EAR 83-13167) to Van Schmus and Bickford.

SOFT ROCKS CAN PROVIDE HARD ROCK ANSWERS

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ABSTRACT

The portion of the province presently covered by Phanerozoic sediments is poorly understood by mineral geologists interested in the Precambrian basement largely because of the paucity of data available. Two methods of data accumulation are presently popular. Firstly, approximately 183 Petroleum and Natural Gas drillholes penetrate through the Phanerozoic into the underlying craton; of these, only 46 have had cores cut in the basement. This first method can provide broad generalizations concerning the nature of the craton and establish regional age relationships. Secondly, various geophysical techniques such as aeromagnetic and gravity surveys reveal broad patterns of cratonic segregation.

A third method of obtaining an understanding of the cratonic basement in the southern portions of the Province is available. This method involves the careful sedimentologic and stratigraphic analysis of the Phanerozoic succession itself using the techniques developed by subsurface "soft-rock" geologists in their search for oil and gas. Three primary assumptions allow the usage of subsurface techniques to understand the nature and evolution of the craton. The first assumption is that the segments which compose the craton have not been quiescent during the Phanerozoic; rather, these segments have undergone movements and structural adjustments from early Precambrian time to the Holocene. The second assumption is that epicratonic basins are predisposed to shallow water, epeiric processes of sedimentation. Such processes are sensitive to even minor variations in basin paleobathymetry. Thirdly, basins which undergo epeiric sedimentation tend to record within their sediments paleobathymetric variations through time, with dominant (i.e. basement influenced paleobathymetry) trends distinguishable from non-basement trends if care is taken in understanding the sedimentology and the depositional history of the rocks themselves. Variations in the dominant paleobathymetric and paleoenvironmental trends through time are a reflection of cratonic activity through time.

The above assumptions allow a geologist to use the Phanerozoic sediments to extract information concerning the underlying craton. Of particular interest to the geologist would be seven "soft rock" characteristics. Firstly, the shifting of sedimentary depocenters, especially in rock units known to be deposited under epeiric influences, records cratonic activity and may aid in distinguishing between individual cratonic segments. Closely allied with the first method is the second, namely the distribution of lithofacies within the epeiric unit. Patterns of erosion, especially persistent erosional trends, is the third. Careful analysis of recognizable local basement-influenced structures can reveal much information with respect to cratonic activity in space; and time. Fifthly, the various fluids contained within Phanerozoic reservoirs contain information of significance, especially the distribution of subsurface brines and the discrimination of discrete physico-chemical fluid regimes. Sixth, certain drillholes have either penetrated or closely skinned basement-involved structures; the analysis of these well cuttings, cores, and geophysical logs often reveals a wealth of information. Seventh, and final, is the process of evaporite solution. Evaporite solution is a process driven by deeper tectonic disturbance and a conduit system controlling both sedimentation and subsurface fluid circulation.

The mineral explorationist searching the portion of the Province overlain by Phanerozoic sediments would do well to consider the techniques and methods of the oil and gas explorer. By utilizing Petroleum and Natural Gas subsurface data, the minerals geologist taps into a vast wealth of useful information if the framework for the proper analysis of those sediments is in place. The most important aspect of using soft-rock data and techniques is the perception of the geologist working with such material.

NEAR SURFACE MINERAL POTENTIAL OF THE PLAINS OF WESTERN CANADA, WITH SPECIAL REFERENCE TO SASKATCHEWAN

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ABSTRACT

With the recent discovery of diamondiferous kimberlite in the Prince Albert area, southern Saskatchewan, the entire plains area is being viewed with renewed exploration interest. Thus, exploration activity has grown from being concentrated in the northern part of the province (primarily the Precambrian Shield) to include the southern part of the province where the geologic conditions are radically different.

Immediately south of the Shield, bedrock consists of relatively hard rocks that were little deformed by the overriding ice sheets. Here the thickness of glacial sediments is tens of metres and the stratigraphy is relatively simple. Farther south, bedrock comprises soft, deformable sediments, the drift is commonly hundreds of metres thick, and the stratigraphy is complex. An understanding of Late Cretaceous, Tertiary and Quaternary geologic environments and deposits that have undergone subsequent erosion, transport, and deposition is crucial to effective exploration.

Kimberlites are known to intrude rocks as young as the Ashville Formation. Gold is found in preglacial gravels and other aggregate deposits, along with minerals such as garnet and magnetite. Industrial minerals such as clays, bentonite, silica sand, and building stone are exposed at various locations throughout Saskatchewan.

A database, compiled over the last 30 years, provides the foundation of this new exploration focus. New approaches in utilizing this data could result in new mineral development on the Prairies.

INTRODUCTION

The recent discovery of diamondiferous kimberlite in the Prince Albert area has led to renewed exploration activity in the Plains of Western Canada. This paper is intended to review the potential of selected mineral resources in that part of western Canada, primarily Saskatchewan, underlain by Phanerozoic rocks.

Most of the area was covered by continental ice sheets several times during Quaternary time. As the Quaternary geological conditions are very different from those encountered in the Precambrian terrain

in the north, this paper will address some problems encountered in the south. Exploration techniques that can be used throughout the region will be discussed briefly, but the main focus is to identify some potential economic mineral resources and problems that might be encountered during an exploration program.

For the purposes of this paper, 'near surface' is defined to be within approximately 100 m of the present land surface or to the base of the drift. It is recognized that this arbitrary depth is clearly too great for economic recovery of many resources such

as clays and aggregates. Also, in some areas the bedrock surface occurs at depths greater than 100 m.

GEOLOGICAL SETTING

Bedrock Geology

The plains of southern Saskatchewan, Alberta and Manitoba and adjacent areas of the United States lie within the Western Interior region of the North American continent. During much of Cretaceous time an epicontinental sea occupied this area. Strata, resulting from the deposition of sediments derived from the uplifting highlands to the west, preserve a record of alternating marine transgressions and regressions. The regional pattern of sedimentation, intertonguing marine and nonmarine sediments, has proved to be very consistent throughout the Western Interior (Caldwell, 1968).

The regression of the Bearpaw sea marks the end of recognizable marine influences in southern Saskatchewan and Alberta with the sediments of the uppermost Cretaceous (Eastend - Frenchman Formations) and Paleocene (Ravenscrag Formation) all having been deposited in an easterly advancing delta or on the subsequent alluvial plain (Whitaker *et al.*, no date).

Younger, dominantly fluvial sediments, primarily consisting of gravels and sands, but also lacustrine silts and clays, were deposited at various intervals throughout the Tertiary and Early Quaternary until the onset of glaciation. The oldest of these units, such as the Cypress Hills Formation (Eocene-Miocene) and the Wood Mountain Formation (Miocene) cap bedrock uplands in southernmost Saskatchewan. In central Alberta similar sediments are found in the Swan Hills (Oligocene) and Hand Hills (Pliocene) Formations. Younger deposits in Saskatchewan, such as the 'Wynard Formation' and the 'Bredenbury Formation', informally named by Christiansen (1970, 1981), occur farther towards the northeast at lower elevations on the bedrock surface. A generalized correlation chart illustrating the stratigraphic nomenclature employed for the bedrock units in southern Saskatchewan is presented in Figure 1.

A stratigraphic section illustrating the relative thickness of some of these units is shown in Figure 2.

Bedrock Surface Topography

The bedrock surface topography over much of southern Saskatchewan is dominated by large, buried valleys interspersed with gentle concave surfaces eroded by continental ice-sheets. The preglacial drainage system of southern Saskatchewan is recorded in a series of east or northeasterly-trending buried valleys. These valleys are truncated by the northwest - southeast-trending Hatfield Valley, which was formed by fluvial erosion immediately preceding the first glaciation (Christiansen *et al.*, 1977). Buried valleys formed subglacially as tunnel valleys have also been documented (Christiansen, 1987). In the highest parts of the Cypress Hills and Wood Mountain uplands, which were never glaciated, the Late Ter-

AGE M.Y.	SYSTEM	SERIES	SOUTHERN SASKATCHEWAN	NEAR SURFACE MINERAL DEPOSITS
.01	Quaternary	Holocene	Alluvial Deposits	Placer Minerals Sand, Gravel
1.8		Pleistocene	Glacial Drift	Sand & Gravel
5	T E R T I A R Y	Pliocene	Empress Gp.	Placer Minerals
			Bredenbury Fm.	
		Miocene	Wood Mountain Fm.	Clay
		Oligocene	Cypress Hills Fm.	Silica, Sand & Gravel
23	T E R T I A R Y	Eocene		
37				
55		Paleocene	Ravenscrag Fm.	Bentonite, Kaolin
65				
70	C R E T A C E O U S	Upper Cretaceous	Frenchman Fm.	Bentonite Kaolin
			Battle Fm.	
			Whitemud Fm.	
			Eastend Fm.	
			Bearpaw Fm.	Bentonite
			Judith River Fm.	
			Lea Park Fm.	
			Upper Colorado Gp.	
140	S I L U R I A N	Lower Cretaceous	Lower Colorado Gp.	Silica Sand Kaolin
			Manville Gp. Swan R. Fm.	
400	O R D O V I C I A N		Interlake Fm.	Diamonds
435			Stonewall Fm.	
			Stoney Mountain Fm.	
			Red River Fm.	
			Winnipeg Fm.	
600	Precambrian			Building Stone Dolomite

Figure 1 - Correlation chart of geological formations exposed in southern Saskatchewan and adjacent areas and potential mineral deposits (modified from Caldwell, 1987).

tiary landscape is preserved on the plateaux, the upper reaches of the valleys heading on the plateaux, and the upper parts of pediments along the south-facing slopes (Klassen, 1987).

In northern Saskatchewan the bedrock surface may have been little modified by the various glaciations that affected it. As a result, the bedrock surface topography is essentially the same as that prior to the onset of glaciation. In contrast to the crystalline rocks forming the bedrock surface in northern Saskatchewan, which are not easily deformed, the sequence of soft, sedimentary rocks that form the bedrock surface in the south is relatively deformable.

In the south the bedrock surface has been further modified by deformation or thrusting of the soft sediments by glacial ice. The result of these processes can be either ice-thrust ridges, such as in the Dirt Hills (Christiansen and Whitaker, 1976), or ice-thrust depressions, as is the case at Fire Lake (Christiansen and Sauer, 1988). Typically, there is no surface expression of ice-thrust features.

Collapse, due to the removal of salt in the Prairie Evaporite Formation, has also affected the bedrock surface in southern Saskatchewan and northeastern Alberta. Collapse features have been documented at several places in Saskatchewan (Christiansen, 1967, 1971).

Glacial Geology

The drift thickness is extremely variable throughout the glaciated portions of Saskatchewan. It ranges from 0 m throughout much of the shield region to more than 300 m in the Touchwood Hills. Drift thicknesses of 100 to 200 m are not uncommon in southern Saskatchewan. The difference in drift thickness between northern Saskatchewan and southern Saskatchewan can be attributed, in part, to the bedrock geology; the hard, crystalline rocks of the Shield are much more resistant to erosion than are the soft, sedimentary rocks of southern Saskatchewan.

The Quaternary stratigraphy in northern Saskatchewan is relatively simple. Here, most of the drift is related to the last major glacial event. In southern Saskatchewan the stratigraphy is very com-

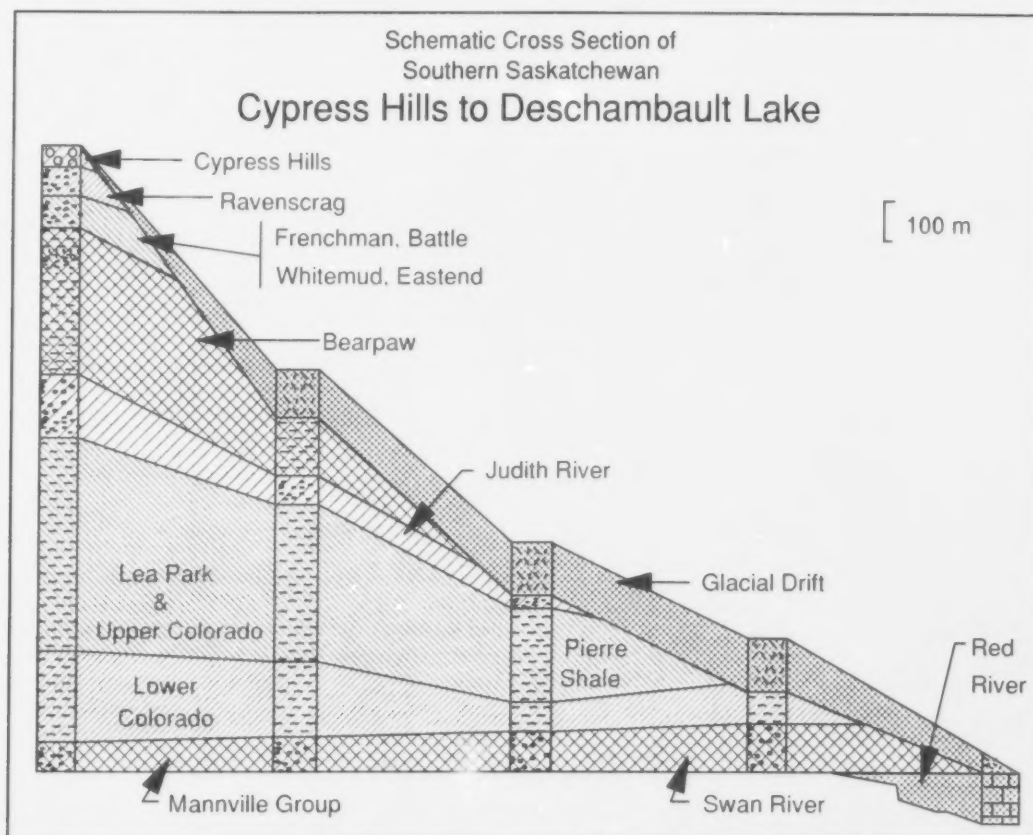


Figure 2 - Schematic stratigraphic section of formations exposed in southern Saskatchewan.

plex, with sediments deposited during at least six major glacial events, and associated non-glacial deposits being preserved.

The Empress Group (Whitaker and Christiansen, 1972) comprises fluvial sands and gravels and lacustrine silts and clays that occupy the stratigraphic position between the bedrock and the lowest till. In Saskatchewan, these sediments occur primarily as fill in the buried bedrock valleys. The Empress Group is Late Tertiary to Quaternary in age as evidenced by the lithology of the sediments: the lower part consists of preglacial material derived from a western provenance, such as chert and quartzite clasts, whereas the upper part contains shield material, such as igneous and metamorphic clasts, deposited by meltwater in front of the advancing ice-sheet. The sediments that comprise the Empress Group in the Hatfield Valley fall into the latter category. Preglacial gravels have several common characteristics that make them identifiable; they rest directly on bedrock, contain no Canadian Shield rocks and are overlain by till (Stalker, 1968). Deposits can be very large and continuous and may occur at any elevation.

The Sutherland Group (Christiansen, 1968a) comprises three till units (Christiansen, 1983) and their associated inter- and intraglacial sediments. The Saskatoon Group (Christiansen, 1968a) includes the Floral Formation, which itself includes at least two tills and associated non-glacial units, the Battleford Formation (Christiansen, 1968b), which is the uppermost till in west-central Saskatchewan, and post-glacial sediments that are collectively, though informally, known as Surficial Stratified Drift. In addition to weathering horizons and oxidation zones, which are sometimes preserved at the top of an individual unit, the tills can be differentiated by carbonate content, geophysical signatures, and material properties. Tills of the Saskatoon Group generally have an increased carbonate content, show increased resistivity (R) and spontaneous potential (SP) responses on electrical logs, and contain more sand and silt than do tills of the Sutherland Group. Figure 3 shows the geological and electrical logs of a testhole along with the data obtained by carbonate analyses of the till and the resultant stratigraphic interpretation.

MINERAL POTENTIAL

Kimberlites

Diamondiferous kimberlite pipes are known to occur in central Saskatchewan where they intrude Cretaceous sediments at least as young as the Ashville Formation. It is postulated that these pipes emanate from fissures in the Precambrian bedrock and likely follow structural weaknesses in the overlying

bedrock toward the surface. Numerous subsurface structures have been identified by test drilling and geophysics. Many of these features are associated with collapse due to the dissolution of the underlying Prairie Evaporite Formation. However, a number of these features do not have characteristics which indicate this origin. For example the structural phenomenon near Viewfield in southeastern Saskatchewan has been attributed to a buried meteor crater (Sawatsky, 1972). At Elbow near Lake Diefenbaker, a structural feature has been identified through drilling and geophysics. A structure such as this, as well as other structures, suggest another mechanism of formation which may be associated with intrusions.

Such structures may have no surface expression while others may be traced to surface features. Major lineaments, which can be identified on the ground surface, may be reflections of these structures and therefore are an element in defining an exploration target.

Although the pipes can occur at the bedrock surface, little is currently known about how much of the pre-existing bedrock and intrusive rock was removed by preglacial and glacial erosion. Based on a series of consolidation tests of Cretaceous bedrock samples throughout Saskatchewan, it is estimated that as much as 1000 m of material may have been removed prior to glaciation (Sauer, 1988). Coal rank studies in Alberta indicate that between 900 and 1900 m of sediment has been removed (Nurkowski, 1984).

Most of the bedrock material was likely eroded during the preglacial period, largely by fluvial erosion. Preglacial valleys such as the Battleford, Tyner and Swift Current valleys, therefore, could contain remnants of the eroded upper bedrock materials including indicator minerals from the kimberlite pipes. The Hatfield Valley, which truncates many of the older preglacial valleys, would be a major collector of these materials; however, the redistribution of these indicators may make tracing the source difficult.

Glaciation did have a significant effect on the prairies in a depositional sense. Multiple glacial events resulted in thick sequences of glacial and interglacial sediments arranged in a complicated stratigraphic sequence. The tills that lie on the bedrock surface reflect the bedrock lithology most closely as the source material for the tills. Successively younger tills, higher in the stratigraphic sequence, reflect the bedrock source to a progressively lesser extent. Weathering profiles preserved on many of the till surfaces suggest that glacial erosion was not extreme on the underlying or previously existing till sheets; therefore, incorporation of significant amounts of the till being overridden is not common. The till units are significantly different in lithology

and retain these characteristics throughout the extent of the deposit.

In some places glacial quarrying and thrusting are evident, particularly in some wide belts normal to the ice-flow direction. In these zones large slabs of bedrock, till, or both, may be sliced off and displaced above younger units. An example of the result of this mechanism is Red Deer Hill south of Prince Albert. A testhole drilled on top of the hill intersected a repetition of glacial and bedrock units which are both stratigraphically and topographically anomalous. Presumably, slabs of bedrock containing kimberlite could be thrust into higher positions in the drift resulting in an displaced occurrence.

Between glaciations, as well as during and after the final deglaciation, a great deal of water eroded existing materials and redeposited these sediments as channel fills, outwash blankets, and alluvial fans and terraces. These deposits may contain trace amounts of precious minerals and kimberlite indicators. The coarser sediments resulted in sand and gravel deposits that are used for aggregate, but also may be the best source for these mineral concentrations.

Placer Minerals

Occurrences of placer gold were first discovered along the North Saskatchewan River in 1859 and have been worked intermittently ever since. Placer gold has also been reported from three other areas in southern and central Saskatchewan; along the Waterhen River, the Pasquia Hills, and in the Wood Mountain area, although there was little, if any production from these areas (Coombe, 1984).

A recent interpretation of new and existing data (Cheel and Leckie, 1989; Leckie and Cheel, 1989) indicates that the sediments comprising the Cypress Hills Formation in southwestern Saskatchewan and southeastern Alberta may have been deposited by streams flowing north - northeasterly from auriferous areas in what is now Montana. Although some preliminary sampling of the gravels in this formation has been conducted, the potential for these sediments to contain gold is not yet known.

Preliminary sampling of Empress Group sediments exposed and in the subsurface along the preglacial Tyner Valley have yielded encouraging results. A grab sample obtained along the South Saskatchewan River several kilometres upstream of the confluence with the Red Deer River graded 27 ppb (0.001 oz/ton) and yielded 37 gold grains. The gold grains ranged in size from 0.02 mm to 0.4 mm. The sample was obtained from the chert and quartzite gravel approximately 2 m above the erosional contact with the Judith River Formation. Geological sections through

the site (David and Whitaker, 1973; Millard, 1989) indicate that this is approximately 75 m above the lowest elevation at which Empress Group sediments occur in the area. Farther east, near Saskatoon, a testhole drilled in 1987 encountered Empress Group sediments between approximately 75 and 155 m. Here, a composite sample taken over a zone approximately 30 m thick graded at 4 ppb and yielded 5 gold grains. These varied in size from 0.02 to 0.12 mm.

Gold production has been recorded in Alberta since 1887 (MacGillivray *et al.*, 1985) from placer operations, principally on the North Saskatchewan River. Highest recovery of gold, however, was reported in 1980. This production is the result of by-product extraction, not from surface sands and gravels, the traditional source, but from preglacial gravels (Saskatchewan Sands and Gravels, or part of the Empress Group) that occur in upland areas.

The Alberta Research Council has determined that the presence of gold is widespread in the preglacial gravels of Alberta, and this occurrence appears to extend into Saskatchewan. Values are reported in deposits across Alberta from northwest of the City of Peace River to the Hand Hills in south central Alberta and into Saskatchewan at Empress. Gold occurs in the preglacial sediments in essentially the same size and concentration as that in modern rivers. The gold is extremely fine, averaging about 0.13 to 0.14 mm in size and occurs in very low concentrations, ranging from 0.001 to 0.016 oz/ton. In a separate analysis at a major gravel plant in the Edmonton area (Romaniuk, 1981), assays ranged from 0.0012 to 0.00276 oz/ton in various processed fractions of the sand and gravel, including the tailings after the material was sluiced. Beneficiation is currently in the form of conventional sluicing on the pit run material before processing or on various sand fractions after processing.

All of the producers reporting gold recovery were in the Edmonton area and were generally located in the Saskatchewan sands and gravels. Smaller amounts of platinum were also recovered.

It has been demonstrated that more effective extraction of the fine gold is possible. A comparison of conventional sluice box against a jig reported that 75 percent more gold was recovered, especially in the finer grain sizes. Recovery below 28 mesh was 150 percent higher than in the sluice box system (Placer Mining Research Program, 1986). Together, widespread distribution and potential for higher recovery using more effective equipment suggest that there is opportunity for increased recovery of fine gold and, perhaps, platinum on the prairies.

The minerals magnetite, garnet, and quartz are much more common components of sand and gravel deposits. Small amounts of magnetite are presently being recovered for coal processing and specialty markets. Garnets may find more use in the blasting sand market and have several natural advantages over silica sand. In Alberta, less than five percent of the sand and gravel mined is processed for gold and platinum, and virtually none is processed for magnetite and garnet, although all of these minerals are known to occur and can be sold.

Industrial Minerals

Sand and Gravel

Sand and gravel resources support a large and well-developed industry on the prairies. More granular materials are mined in Alberta annually than any other province except Ontario. Together, Alberta and Saskatchewan produced an estimated 58.2 million tonnes of sand and gravel in 1987, worth about 170.8 million dollars (Canadian Minerals Yearbook, 1987). Yet, the real potential of the material mined in terms of mineral value has yet to be realized.

Sand and gravel deposits in Saskatchewan are, for the most part, a direct result of the last glaciation. Large deposits of sand and gravel accumulated in the proglacial environment as outwash plains and meltwater channel deposits. A great number of smaller deposits were formed as ice disintegration features including kames, eskers, and crevasse fillings. Deposits of this type are generally smaller, more numerous and widespread, and highly variable in composition. Kame complexes can, however, be quite extensive and contain large quantities of usable aggregate.

Exploration and testing of hundreds of deposits by the Saskatchewan Department of Highways and others have shown that most deposits tend to be gravelly sand, that is, more than 50 percent sand with lesser amounts of gravel size material. Only about 1 in 10 deposits contain more than 50 percent gravel size material. Moreover, even the coarse deposits usually contain relatively little material that is over 4 cm in diameter.

It is difficult to generalize on the distribution of the many sand and gravel deposits scattered throughout the province. It is likely that a few gravel deposits scattered widely across Saskatchewan contain more than 50 percent of the known gravel reserves. Smaller deposits will, however, continue to be exploited as transportation costs are usually the critical factor to deposit development. Production of sand and gravel in Saskatchewan for 1988 was reported to

be approximately 10 million tonnes with a value of 30 million dollars.

Quartz as silica sand from aggregate deposits may be a difficult commodity to market because of large volume and high quality competitors, but washed and sized silica sand can be sold in small quantities, increasing the selling price by 10 to 100-fold.

Silica Sand

There are a number of deposits of fairly clean silica sand in Saskatchewan. These deposits are, for the most part, either undisturbed or reworked portions of the Swan River Formation of Early Cretaceous age.

The best known exposures of the Swan River sands, are four along the Red Deer River in east central Saskatchewan. Reserves have been estimated in the order of 9 million tonnes. Silica content is reported to be approximately 98 percent with traces of Al, Fe, Ti, Ca, and Mg (Guliov, 1984).

The Wapawekka deposit is located approximately 45 km southeast of La Ronge, on the shores of Wapawekka Lake. This deposit is another outcrop of the Swan River sand, but further north and more inaccessible. Reserves have been estimated in the billions of tonnes. This estimate includes material which underlies nine townships in the down dip direction of the deposit, and would be covered by greater thicknesses of overburden. In spite of the apparent vast reserves of material, little development of the resource has occurred.

Clay

Kaolin

The bulk of Saskatchewan's kaolinite-based clays occurs in a band just north of the U.S. border, specifically in the Cypress Hills, Wood Mountain, Willowbunch, and Estevan regions. Clays of commercial and industrial significance in these areas are of two ages: 1) those in the Willowbunch Member of the Ravenscrag Formation, which comprise a variety of clays of earthenware quality including some stoneware and low-grade refractory clays, and 2) those from the upper part of the Whitemud Formation comprising the plastic stoneware clays, ball clays and refractory clays lying on kaolinitic sandy clays of the lower part of the Whitemud Formation. A major clay products industry in the Medicine Hat area, Alberta, has existed since 1910 and has maintained interest in the region for the location and development of raw materials (Lindoe, 1984).

The Whitemud Formation consists of a sandy clay member which contains much kaolinite close to its base, a more or less carbonaceous central zone, and

a zone enriched in plastic clays - ball, fire and stoneware - at its top. The kaolinite content may reach 50 to 55 percent in some Wood Mountain area occurrences, but is commonly less. The Whitemud Formation extends in scattered outcrops from Eagle Butte on the west side of the Cypress Hills in Alberta, to the Big Muddy Valley in Saskatchewan. Reserves of nearly 400 million tonnes of kaolinized sediments have been proven by Ekaton Industries who plan to begin production in the Wood Mountain area (Master, 1987).

Saskatchewan has some of the highest grade and largest clay deposits in Canada. Yet production of clay and clay products in Saskatchewan represents less than 3 percent of the national total value.

Bentonite

Non-swelling, calcium bentonite occurs in the Vermilion River Formation (Upper Cretaceous), the largest known deposit being on the Swan River north of Pelly (Winer, 1954). Small deposits have been located south of Moosomin, but none of commercial size. Other non-swelling bentonite is found west of Rock Glen in the Ravenscrag Formation.

Swelling sodium bentonite occurs in the Ravenscrag Formation in an area extending from the east end of Twelve Mile Lake to St. Victor and further to the southeast in the Big Muddy Valley.

South of Wilcox, in the Blackfoot Ridge badlands, swelling bentonite is mined from beds fairly high in the Bearpaw Formation by Avonlea Mineral Industries Limited. Here there is essentially no glacial drift, but the strata are broken up into a jumble of fault blocks of various orientations through the effects of glacial thrusting, and are further complicated by subsurface salt-solution collapse effects.

A few kilometres south of Wilcox large reserves of swelling bentonite have been proven. Overburden is thick (about 6 m) and essentially continuous. Bentonite occurs discontinuously in two beds separated by about 3 m of shale. In 1986 Canada imported approximately 340,000 tonnes of bentonite mostly from the United States. Canadian bentonite production was reported as approximately 88,000 tonnes.

Stone

Dolomite of Ordovician and Silurian age outcrop in east-central Saskatchewan immediately south of the Precambrian Shield. Studies are currently underway in a number of locations to evaluate the material for building stone. A quarry was recently opened to produce dolomite for use on the University of Saskatchewan's new Agriculture building. This is the first recorded bedrock quarry for the production of

building stone in Saskatchewan. Local stone has been used in building construction in Alberta since the turn of the century.

EXPLORATION

Databases

An effective exploration strategy in southern Saskatchewan will initially involve a comprehensive assessment of all available maps, databases, and reports. Testhole logs are continually being collected for geological and hydrogeological investigations. At present 3,000 logs from exploration testholes drilled under supervision of a geologist are on file. Most of these testholes are drilled into bedrock. These logs are composed of a geophysical log and a lithological description. Single point resistance and spontaneous potential are the two common electric logs. More recent testhole logs include natural gamma and caliper logs. In all cases the lithology of the geologic units is described based on the description of samples collected at regular intervals such as 1.5 or 3 m.

Approximately 6000 water well logs are on record with this number increasing constantly as new wells are drilled through the testhole assistance program offered by the Saskatchewan Water Corporation. These logs include electric logs similar to the testhole logs described above. A driller's description is the only lithological determination of the units encountered. Some of these wells are drilled to bedrock but many are shallow, being completed in an aquifer within the glacial deposits.

In addition to these holes drilled in the drift there are over 9000 logs from exploration drilling for potash, oil, etc. These holes are commonly very deep, showing the bedrock geologic units. The logs are composed primarily of geophysical logs of various types; however, the upper part of the hole is commonly cased which prevents or restricts the effectiveness of the geophysical logs within the drift. Formation tops may be identified on some of these logs.

A water quality database containing over 4000 records is available along with a database of aggregate deposit information. Various other forms of analytical and interpretive information are also available. Reports describing the shallow bedrock and glacial geology have been written for a number of areas in the form of Saskatchewan Department of Mineral Resources (now Saskatchewan Energy and Mines) reports, and Geological Survey of Canada reports, SRC reports, or as university theses.

Similar types of data are available in Alberta: water well logs from Alberta Environment, and geological and aggregate data from the Alberta Research Council. Alberta has been extensively drilled during the course of petroleum exploration; about 145,000 wells provide an extensive source of subsurface data. Coal exploration also provides an extensive database in much of the province.

Information

This information is routinely compiled and interpreted in order to construct a series of maps and reports which define the deposits. A series of surficial geology maps showing the surface materials and landforms has been compiled for southern Saskatchewan. Aggregate potential maps are derived from these surficial geology maps as an aid in exploration and development of aggregate resources. A series of maps at scale 1:250,000 conforming to the NTS system show the bedrock geology and topography and provide some indication of drift thickness. A new series of maps and cross-sections, which depict the shallow bedrock and glacial geological features, is currently in production. Seven NTS areas have been completed. This series includes new maps of the bedrock geology and topography. A pilot project is underway to transform this information into a digital form for easy access, updating and manipulation and ultimately, for use in a GIS system. All these sources of information assist in defining the geological environment and therefore, can be of value in exploration for mineral resources on the prairies. Information on the industrial and metal minerals of Alberta is publicly available as a Hypercard database from the Alberta Research Council.

Methods

Mineral exploration methods in the southern part of Saskatchewan and much of Alberta will vary depending on the resource being sought. However, most exploration will require some means of excavation or subsurface investigation due to the cover of glacial deposits. Commonly, these overlying materials and the shallow bedrock are unconsolidated and are easy to excavate. Standard methods are likely adequate for most exploration cases.

Placer minerals will require surface excavation of materials in relatively large quantities which must be processed in order to concentrate the mineral fraction. Similarly, aggregate deposits require excavation using such equipment as a backhoe or front-end loader. Industrial minerals may also be investigated using such equipment if the overburden is thin. Commonly, truck mounted power auguring is an effective exploration tool where the overburden ranges in thickness from 5 to 30 m. These rigs are very mobile

and use no water for drilling. The samples are large and relatively undisturbed. This makes drilling a series of shallow holes in close proximity very cost effective. For terrain where the drift exceeds 30 m, standard rotary drilling, as used for drilling water wells, should be effective for exploration. Most larger rigs can reach bedrock, which is commonly less than 300 m below surface throughout southern Saskatchewan. The diameter of the hole can range from 12 to 20 cm and can be larger with special equipment. Using the proper drill bit with this size of hole will usually produce adequate samples. For extremely large volumes of material, a sampling program could be designed with the appropriate equipment. Coring can also be accomplished with both the auger and rotary drill. Shelby tubes 8 cm in diameter and 60 cm long, can be pushed with both rigs into these sediments. For longer cores up to 1.5 m, a Denison core barrel or similar apparatus may be used to collect undisturbed cores. Coring using a diamond core barrel can also be carried out for hard material such as consolidated, stoney tills and lithified bedrock.

SUMMARY

The plains of Western Canada have significant mineral potential in precious metals, diamonds and industrial minerals that have not been exploited.

A thorough knowledge of the geological setting of the near surface bedrock and glacial deposits is essential for effective exploration, and interpretation of results of exploration surveys.

The standard tools and methods such as backhoe excavations, auguring or rotary drilling work well in this terrain and can be adapted to be more effective in mineral exploration. Geophysical methods need to be modified or developed to suit this near surface environment. Combining these tools with proper interpretation can result in the discovery and development of mineral resources on the prairies of Western Canada.

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Precious Metal Exploration

REGIONAL- AND DEPOSIT-SCALE CHARACTERISTICS OF STRUCTURALLY-CONTROLLED LODGE GOLD MINERALIZATION IN THE LA RONGE GOLD BELT

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ABSTRACT

During the 1980's, northern Saskatchewan received record levels of gold exploration and development expenditures (approximately \$196 million) ranging from a low of \$3 million in 1982 to an estimated \$65 million in 1988. During this period several exciting new gold discoveries were made (eg. 21 zone, Rod zone, Jasper - James, North Lake, Bakos) while re-evaluation of many known prospects led to substantial increases over previous reserve estimates (eg. Seabee, Tower Lake, Jojay, Pap/Preview). This surge in gold exploration has delineated about 3 million ounces gold distributed between deposits presently in production and those undergoing advance stages of exploration. Over half of the estimated gold reserves in Saskatchewan occur in twelve main deposits (1.74 million ounces gold) in the La Ronge region.

Most gold discoveries in northern Saskatchewan have been in the greenstone belts of the La Ronge Domain and, to a lesser extent, the Glennie and Flin Flon Domains. This region is informally referred to as the La Ronge Gold Belt. In the La Ronge Domain gold deposits are concentrated in four principal areas; Waddy, Tower, Star and Sulphide Lakes. In the Glennie Domain the most significant gold deposit is in the Laonil Lake area. The majority of these gold deposits can be classified as structurally-controlled quartz vein- or lode-type, with a limited number interpreted as structurally modified stratiform-type. Regional and deposit scale characteristics are outlined and discussed for structurally-controlled lode gold mineralization.

Many features characterizing lode gold deposits in the more publicized Archean greenstone belts of eastern Canada are common to the Early Proterozoic La Ronge Gold Belt. There is excellent potential for further gold discoveries in this area of northern Saskatchewan.

INTRODUCTION

This paper first reviews the regional geology of the 'La Ronge Gold Belt' which encompasses part of the Early Proterozoic Reindeer Zone in the southeastern part of the Precambrian Shield in northern Saskatchewan (Figure 1A). The second part describes the inherent physical characteristics of structurally-controlled lode gold mineralization in the La Ronge Gold Belt in order to present a broad empirical model for gold mineralization in this region. The common characteristics are identified and placed in the regional framework to establish criteria for grassroots exploration. Not discussed are the physiochemical nature of the mineralizing fluids, transport mechanism of the fluids to their deposition-

al sites, or probable source of the gold and fluids, and hence a genetic model is not proposed.

On a regional-scale, the gold deposits appear to be fundamentally similar in that they display a marked propensity for the greenstone-plutonic belts and are relatively rare in major metasedimentary belts. They exhibit a higher frequency in plutonic bodies, occur in similar ambient metamorphic environments, and are found within major composite shear or fault systems. At a deposit-scale, there is more variability with respect to the degree of wallrock alteration, deformational regime of the host structures, and style of the mineralized vein systems. The majority of examples are drawn from the Star Lake and Waddy - Tower Lakes areas, with fewer from the Sulphide and Laonil Lakes areas. Table 1 lists the reserves

Table 1 - Published Reserves From Selected Saskatchewan Gold Mines/ Deposits

Owner(s)*	Deposit(s)	Reserves(t) (Unstandardized)	Grade	
			g/t	oz/ton
CAMECO-Starrex Min.-Uranerz Expl. Min.	21 Zone (Star Lake Mine)	208 650	17.2	0.50**
CAMECO-Golden Rule Res.-Int. Mahogany Corp.- Shore Gold	Fork Lakes (Jasper)	125 000	19.2	0.56
CAMECO-Uranerz Expl. Min.- Windarra	Pap SW Bakos	350 000	13.7	0.4
		1 297 000	10.0	0.29
CAMECO-Husky Oil	Laurel Lake	367 000	15.1	0.44
Claude Res.	Seabee	1 013 000	12.5	0.365
Corona Corp.- Int. Mahogany Corp.	Rod (Jolu Mine)	376 480	13.7	0.4
	Mallard	18 350	22.7	0.66
Golden Rule Res.-CAMECO- Goldsil Res.- Comaplex Res.	Tower East	2 725 000	3.4	0.11
Goldsil Res.- Golden Rule Res.-CAMECO	Transom Lake (James-Jasper SW)	77 800	13.0	0.38
Placer-DOME- Waddy Lake Res.- Goldsil	Komis	1 460 000	5.1	0.15
Radcliffe Res.	North Lake	1 179 000	3.8	0.11
Tyler Res.- Golden Rule Res.-CAMECO	Weedy B	400 000	4.5	0.13
	Golden Heart	733 800	8.6	0.255

* Operator first

** Mined out

and grades of the major gold deposits from the La Ronge Gold Belt.

Regional Geology

The regionally extensive Reindeer Zone (Stauffer, 1984) is part of the Early Proterozoic Trans-Hudson Orogen (Hoffman, in press), which comprises a collage of lithostructural domains (Figure 1A and B) representing subduction-generated arc volcanism, plutonism and related sedimentary basins, as well as post-subduction molasse sedimentation. The orogen developed during north-south convergence and collision between the Rae - Hearne and Superior Cratons (Hoffman, in press). The term La Ronge Gold Belt is informally applied to a roughly triangular-shaped area, within the Reindeer Zone, lying between La Ronge, Southend and Flin Flon (Figure 2). This area is underlain by Early Proterozoic

metavolcanic, metasedimentary and plutonic rocks, and minor Archean basement remnants comprising the La Ronge, Glennie, Kisseynew and Flin Flon Domains and the Hanson Lake Block (Figures 1 and 2).

The majority of gold deposits discovered to date occur in the greenstone belts of the La Ronge and Glennie Domains. These domains comprise a series of stacked, variably strained, northwest- to north-dipping tectonostratigraphic packages which contain both bounding and internal high strain zones. Intensely deformed rocks exhibiting varying degrees of strain commonly form bounding structural zones separating the greenstone belts from the adjacent metasedimentary belts (e.g. McLennan Lake Tectonic Zone). Deformational fabrics in these high strain zones reflect heterogeneous strain ranging from moderate (augen structure, well-developed schistosity) through high (flasered structure, slaty fracture cleavage, protomylonite) to locally very intense (mylonite, mylonitic gneiss, phyllonite). Detailed mapping along these tectonic zones revealed a highly complicated interbranching network of shears separated by 'tectonic islands' of relatively undeformed

rocks. One of the most persistent high strain zones is the McLennan Lake Tectonic Zone (Thomas, 1984, 1985a) which occurs along the boundary between the Central Metavolcanic Belt of the La Ronge Domain and structurally underlying, albeit younger, McLennan Group (Figure 1C).

Ambient metamorphic conditions in most of the greenstone belts ranged from upper greenschist to lower amphibolite, and locally middle amphibolite facies. In contrast, the flanking metasedimentary belts commonly exhibit higher metamorphic grades ranging from middle amphibolite to locally granulite facies.

U-Pb zircon ages from the La Ronge and Glennie Domains brackets the main period of volcanism between 1882 and 1876 Ma (Bickford *et al.*, 1986).

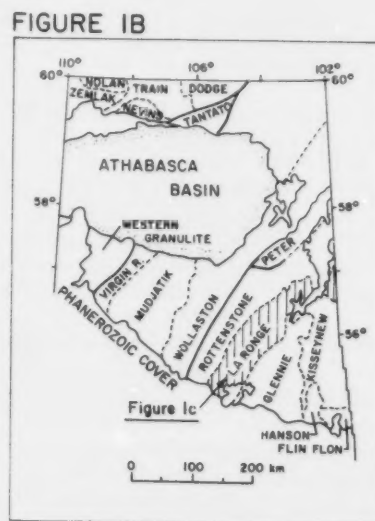
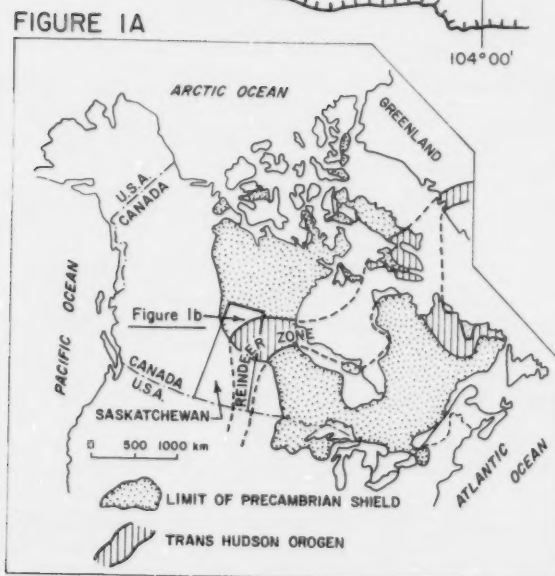
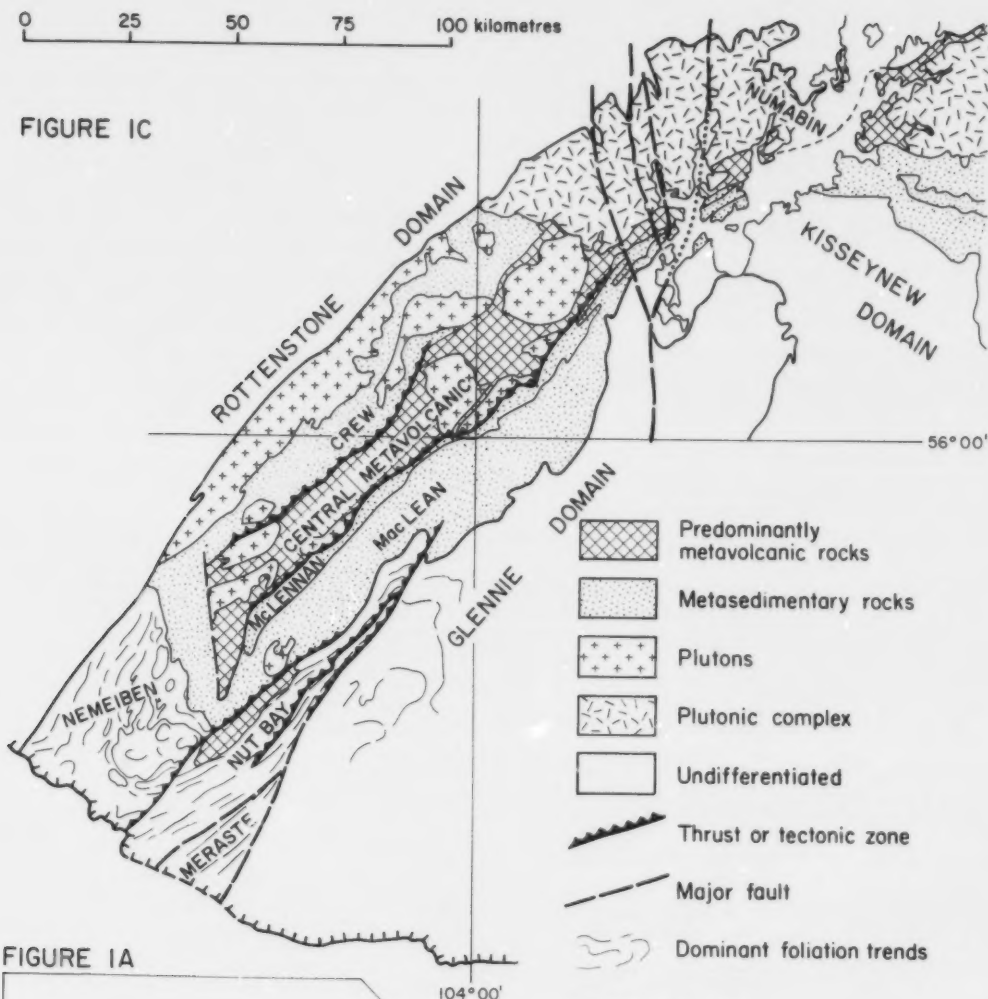


Figure 1 - General location maps. A) Location of the Reindeer Zone and Trans-Hudson Orogen in the Precambrian Shield of North America. B) Location of the La Ronge Domain within the lithostructural subdivision of the Precambrian of northern Saskatchewan. C) Tectonostratigraphic subdivision of the La Ronge Domain.

'LARONGE GOLD BELT'

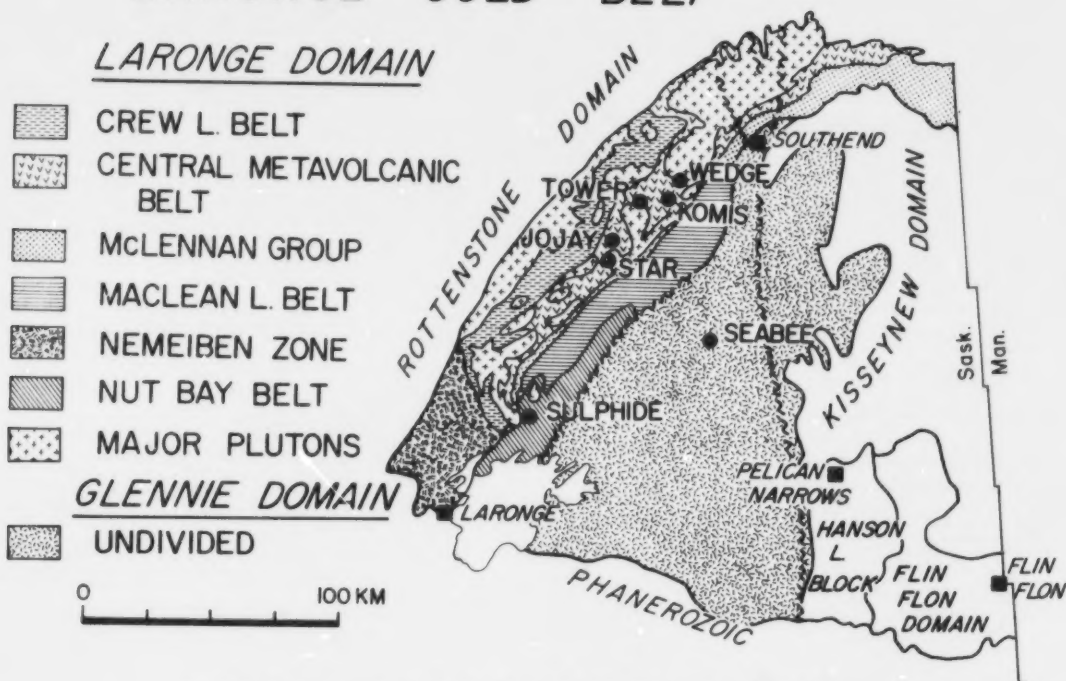


Figure 2 - General location of the 'La Ronge Gold Belt' in northern Saskatchewan.

Radiometric dating by U-Pb zircon method of intrusive rocks from this region indicates major plutonism spanned a period of about 35 million years, from 1866 to 1831 Ma (*ibid*; and Delaney, pers. comm.).

Geology of the Greenstone - Plutonic Belts Metavolcanic Rocks

The greenstone belt successions comprise ultramafic, mafic, through intermediate to felsic subaqueous and subaerial flows and volcanoclastics in varying proportions. Ultramafic volcanics are rare; the most notable occurrence being in the Waddy Lake area (Harper, 1984, 1985, 1986). Mafic compositions are slightly more prevalent than intermediate in most belts; felsic volcanics probably represent less than 10 percent of the successions on average. The proportion of flow versus volcanoclastic rocks can be highly variable within individual belts, however, flow units are probably about twice as abundant on a regional-scale. Geochemically, metavolcanic rocks in the various belts are broadly similar ranging from low-potassium tholeiites to calc-alkaline; however, in the Glennie Domain calc-alkaline volcanics have not, as yet, been identified. Based on field relations, whole-rock chemistry and trace element patterns, most of the major greenstone belts are interpreted to have

formed in an ensimatic island-arc setting, although ensialic environments are reflected by rare earth element signatures in some areas (e.g. northern part of the Central Metavolcanic Belt).

Metasedimentary Rocks

Metasedimentary rocks generally comprise between 10 to 25 percent of the greenstone belt successions, and include greywacke - argillite assemblages, pelite, psammopelite, and minor meta-arkose and metaconglomerate. Mixed silicate - oxide - sulphide facies iron formation, generally associated with major felsic metavolcanic accumulations occur locally in several belts, notably in the Waddy Lake area (Harper, 1984, 1985) of the Central Metavolcanic Belt and the Sulphide Lake area of the Nut Bay Belt (Sibbald, 1986 and Slimmon, 1986).

Intrusive Rocks

Many of the greenstone belts contain an 'early' syn-volcanic intrusive suite of basic to intermediate dykes and sills which commonly display original igneous features such as rhythmic layering, cumulate textures and relict primary mineralogy. They are interpreted as feeder systems within the volcanic pile (Thomas, 1985b; Watters *et al*, 1987). Synvolcanic felsic porphyries, which typically resemble their extrusive equivalents texturally and mineralogically, are iden-

tified by their crosscutting relationships with the surrounding country rocks. The porphyries, which commonly contain feldspar or blue quartz phenocrysts, display miarolitic or degassing cavities locally (eg. along the Star Lake mine road) and autobreccia margins; features which are consistent with their interpretation as high level intrusive bodies.

Major intrusions in the various greenstone belts can be broadly grouped, according to their compositional complexity and their relationship to the country rocks, into three main types: i) composite or multi-phase intrusions ranging from gabbro and diorite to granite, ii) relatively homogeneous tonalitic and granodioritic to granitic plutons, and iii) small, homogeneous intrusions of quartz-rich leucogranite, leucogranodiorite and aplogranite. Peripheral to the major plutons, smaller lens- and plug-like intrusions are common in the supracrustal succession. Geochemically, the intrusions have a calc-alkaline character, and their trace element and Sr-isotope data are consistent with magma generation in a volcanic arc setting (Harper *et al.*, 1986; Thomas *et al.*, 1987). Major intrusions in most belts appear to have been very late to post-volcanic and have been affected to some degree by regional metamorphism and tectonism.

CHARACTERISTICS OF STRUCTURALLY-CONTROLLED GOLD DEPOSITS

The majority of gold occurrences in the La Ronge Gold Belt are classified as structurally-controlled quartz vein or lode gold deposits, with only a few interpreted as structurally modified stratiform-type. On the basis of regional- and deposit-scale studies a number of empirical observations can be made with respect to lode gold mineralization in this region.

1. Strong regional association with major greenstone belts (Figure 3). The majority of gold occurrences are found within the major metavolcanic - plutonic belts (e.g. Central Metavolcanic Belt and Nut Bay Belt), while relatively few occurrences have been found in the major metasedimentary belts (eg. Crew Lake Belt, MacLean Lake Belt, McLennan Group). Within the greenstone belts, gold occurrences are equally distributed between supracrustal and intrusive rocks; however, as intrusive rocks volumetrically compose about 30 percent of the belts, the frequency of gold occurrences is actually greater than in the metavolcanic rocks. The majority of recently discovered gold deposits have been within plutons.
2. Homogeneous competent lithologic units provide the most suitable rheological environment for the development of mineralized structures. Gabbro,

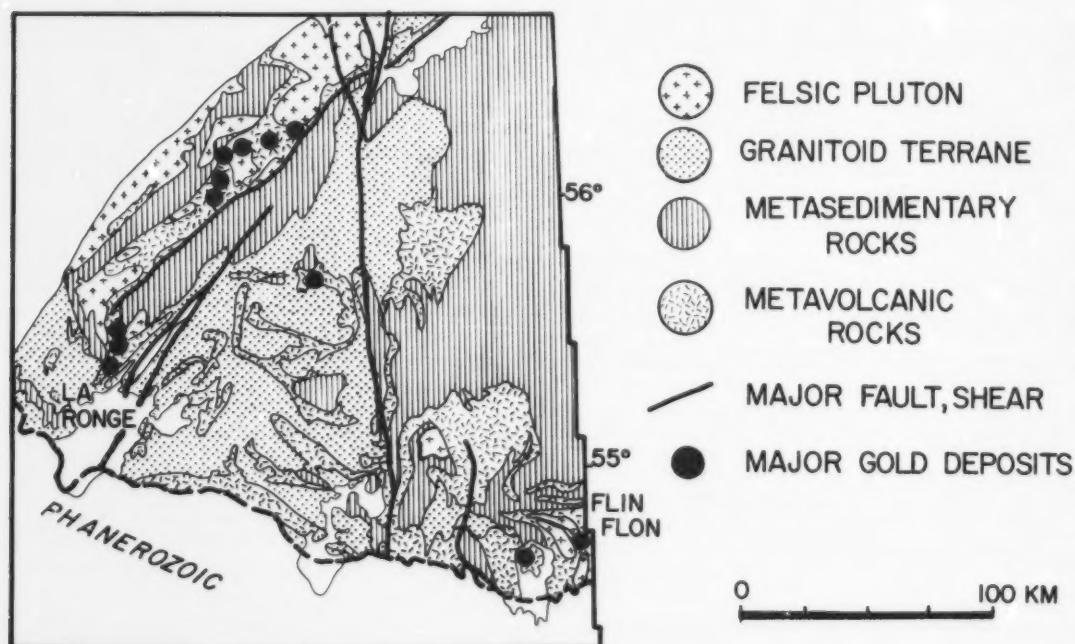


Figure 3 - Distribution of the principal greenstone - plutonic belts and major gold deposits in the La Ronge Gold Belt.

diorite, granodiorite, or granite plutons appear to be the best host environment for the development of mineralized dilational structures. The presence of minor compositional heterogeneities, such as mafic dykes appear to promote initiation and localization of shears and fracture systems in the intrusions.

3. Gold deposits are hosted by rocks which have undergone upper greenschist to lower amphibolite facies metamorphism (Figure 4). The majority of deposits in the La Ronge and Glennie Domains occur in rocks that attained upper greenschist to lower amphibolite facies metamorphism, whereas deposits in the Flin Flon Domain are hosted by rocks of predominantly greenschist facies. Field relationships and mineral assemblages in wallrocks and veins suggest the mineralized systems were emplaced near peak regional metamorphic conditions.

4. Mineralization occurs in subsidiary structures related to major regional-scale structures. Shear zones, faults or broad stockworks of microfracturing play a direct role in localizing mineralization. At a deposit-scale the individual structures range from several hundred metres to several kilometres in

length. These structures are generally subsidiary to or comprise part of larger regional-scale deformation zones which can exceed a hundred kilometres in length. Deposits of the Star Lake area occur within and adjacent to the northeast-trending McLennan Lake Tectonic Zone which can be traced at least 125 km along the southeastern margin of the Central Metavolcanic Belt. The westerly-trending Byers Fault can be traced for about 40 km across the northern part of the belt and forms the locus for a number of significant deposits including the Tower East and West, Weedy Lake, Corner Lake, Oven Lake and Narrow Lake occurrences (Figure 5). In the Laonil Lake area, the Seabee deposit and associated mineralization is hosted in northeasterly-trending shears in diorite, gabbro, volcanoclastics and metasedimentary rocks. The shears are probably second-order structures related to the larger first order Laonil Lake Shear Zone (Delaney, 1986) (Figure 6).

The role of regional deformation zones as areas of enhanced fluid concentration, particularly with respect to gold enrichment, has been discussed by a number of workers (Colvine *et al.*, 1988; Groves *et*

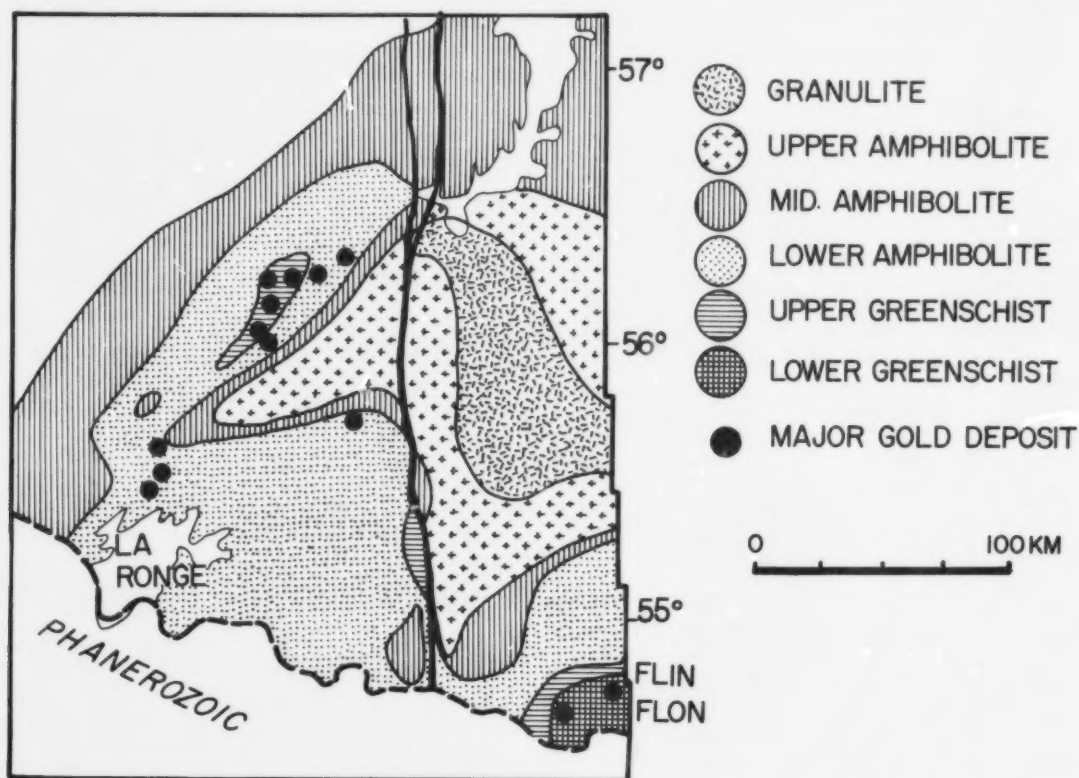


Figure 4 - Regional metamorphic facies map and location of major gold deposits in the La Ronge Gold Belt. Modified from Rees (1982).

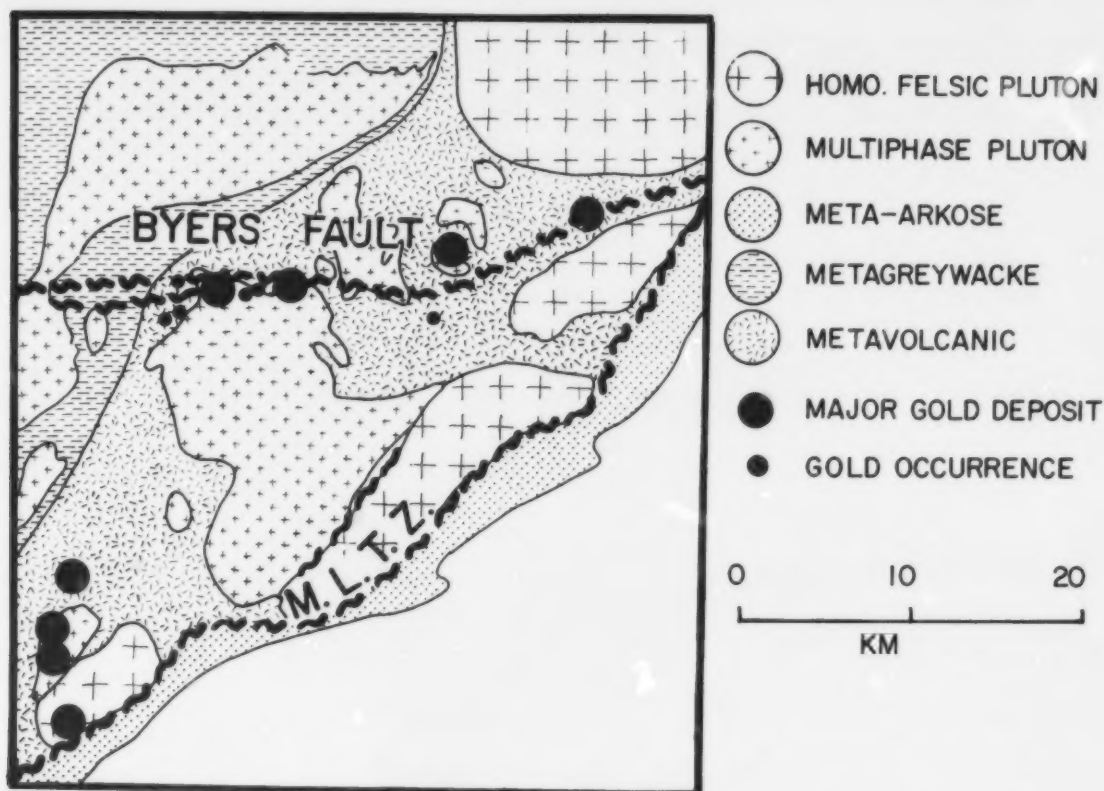


Figure 5 - General geology and location of major gold deposits/occurrences in the Star - Waddy Lakes part of the Central Metavolcanic Belt.

al., 1987; Boulter *et al.*, 1987; Fyfe and Kerrich, 1984). In large-scale transcurrent shear systems the preferred site for fluid concentration is most commonly in zones of increased extension, as opposed to the highly compressional portions of the system (Sibson, 1987; Sibson *et al.*, 1988).

The McLennan Lake Tectonic Zone (MLTZ) is one of the most persistent high strain zones in the region (Figure 7). The zone marks the contact between rocks of the Central Metavolcanic Belt and meta-arkoses of the McLennan Group. It forms a moderate to shallow northwest-dipping complex of anastomosing shears. The bulk of the strain is confined to rocks of the Central Metavolcanic Belt occupying the hanging wall of the structure. The deformational history of the MLTZ is characterized by two main stages. The first event is marked by compressional or transpressional tectonics developing a subvertical stretching fabric primarily preserved in the metavolcanics. This is overprinted by a dominant subhorizontal dextral shearing episode which is largely confined to the trace of the MLTZ and major second-order shears initiated during the first event. The mineralized quartz vein systems are thought to have been emplaced during reactivation of the sub-

sidary structures during this dominantly transcurrent stage.

The coexistence of extensional and contractual zones (e.g. duplexes) along the length of strike-slip systems is not rare (Woodcock and Fischer, 1986), and in the case of the MLTZ may explain the apparent contradictory strain interpretations which have been made for various parts of the zone (Lewry, 1983; Thomas, 1984, 1985b, 1986, 1987; Poulsen *et al.*, 1987). Gold deposits in the Star Lake area appear to be located within a portion of the MLTZ where it widens into a relative broad zone of anastomosing or imbricated faults and shears of an extensional nature; an area highly conducive to increased fluid migration and concentration in strike slip systems. Similarly, if the MLTZ comprises a series of alternating zones of extension and contraction developed during the later strike slip event then an element of predictability exists for recognizing areas of potential mineralization along the zone (Figure 7).

5. Most deposits occur in structures characterized by a transitional brittle - ductile deformational regime. Gold deposits in general occur in structures that possess textural and structural characteristics

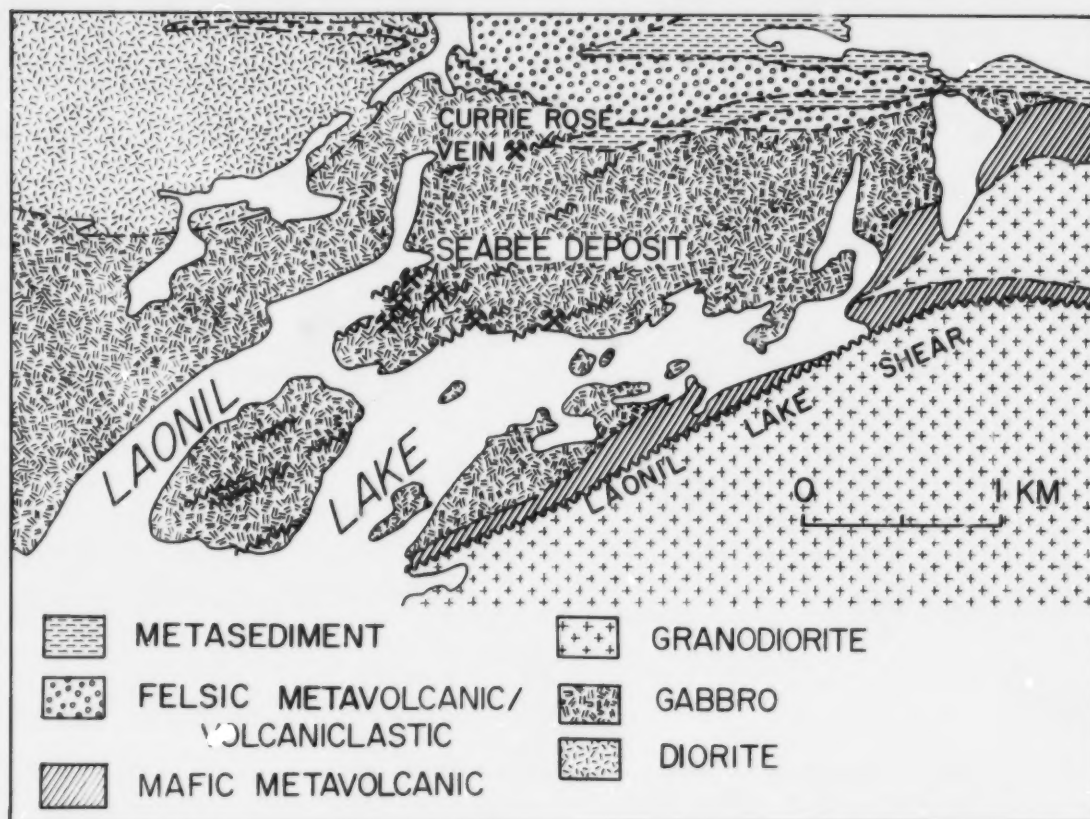


Figure 6 - General geology of the Laonil Lake area, showing distribution of gold occurrences along subsidiary structures probably related to the Laonil Lake Shear Zone (from Delaney, 1986).

that range from brittle through brittle-ductile to ductile regimes, but normally one group of features will be dominant in a deposit. La Ronge Gold Belt deposits occur in structures dominated by the brittle-ductile transition, but some deposits are hosted in brittle settings (e.g. Tower Lake east) and others in ductile settings (e.g. Jasper Pond).

In the Star Lake area the deformational style of the mineralized shears is broadly within the brittle - ductile regime, although a subtle transition from a more ductile deformation in the southern deposits (eg. Jasper - James zone) to slightly more brittle deformation in the northern deposits (e.g. Jolu zone) appears to occur across the area (Figure 8). This subtle transition in the deformational style across the Star Lake area may be due to a number of individual or combination of physiochemical conditions:

i) Progressively higher structural levels are exposed from south to north across the Star Lake area. Deformational zones should display changing characteristics with depth, notably more ductile dominated

environments at depth becoming increasingly more brittle at higher levels (Sibson, 1977; Simpson, 1986; Colvine *et al.*, 1988). Regional metamorphic grade in this area ranges from middle and locally upper amphibolite facies in the southern part, to lower amphibolite and locally upper greenschist facies in the northern part of the Star Lake area. This metamorphic gradient may also reflect, although not unequivocally, differing structural levels across the Star Lake area.

ii) Variations in pore fluid composition, volume and pressure and their reaction with different wallrock lithologies can influence the deformational style, affect the stability of minerals in the wallrocks and hence the wallrock ductility (Colvine *et al.*, 1988). Significant compositional differences between mineralizing fluids is not indicated by the bulk compositions of the veins other than slight variations in their sulphide minerals, notably the pyrite to pyrrhotite ratio. The majority of deposits lack a distinct alteration halo which suggests negligible fluid-wallrock reaction occurred during mineralization. An exception is the

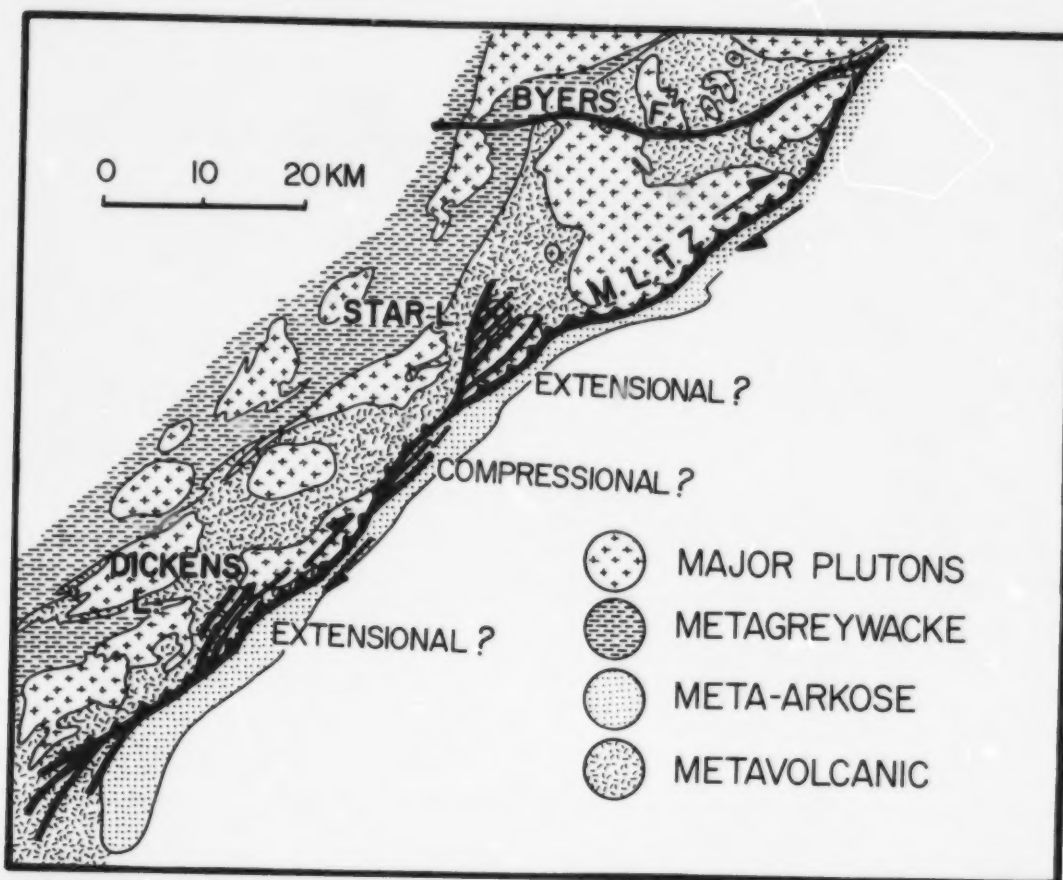


Figure 7 - General geology of the Central Metavolcanic Belt illustrating possible sites of extensional and compressional strike-slip deformation along the McLennan Lake Tectonic Zone (MLTZ).

Jasper - James zone, possibly the most ductile shear system, which has a distinctive tourmaline - muscovite - sericite alteration halo varying from 1 to 2 metres wide.

iii) The response of shearing on different lithologies. Significant compositional differences do not occur between most of the deposits. The Jolu (Mallard Lake zone), and in part the Rod Zone, are hosted by dioritic rocks whereas the other deposits are hosted by granitic to granodioritic rocks of either the Star Lake or Island Lake Plutons. The more ribbon-like nature of the veins in diorite-hosted deposits compared to the somewhat thicker lense-like quartz veins in the granite-hosted deposits (eg. 21 Zone) may be due to compositional differences in the country rock.

6) The mineralized vein systems appear to have been emplaced within the structures during a single protracted deformational history. The mineralized zones are typically composed of composite or multiple quartz veins that form elongate lozenge-shaped

ore bodies developed between the shear zone boundaries. Quartz veins are commonly developed where structural and compositional irregularities occur within the shear zone. Favourable structural sites for vein systems are the intersection of conjugate or branching shear splays and major flexures or irregularities in the shears. Compositional variations, which provide favourable sites, include the intersection and incorporation of dyke material within the shears (e.g. 21 Zone) and where shears cross the contact between major lithologies (e.g. Rod Zone, Mallard Lake zone, Currie Rose vein at Seabee).

The quartz veins typically occupy low angle shear planes (P) and more commonly the central shear plane (D) in the shear zone (Figure 9). En echelon sets of massive quartz-filled tension gash veins occur as late fracture fillings across shears in some deposits (e.g. Jasper - James) but are not particularly common. In underground exposures at the Star Lake and Jolu mines, early developed shear veins and tension gash veins are commonly folded, offset by small

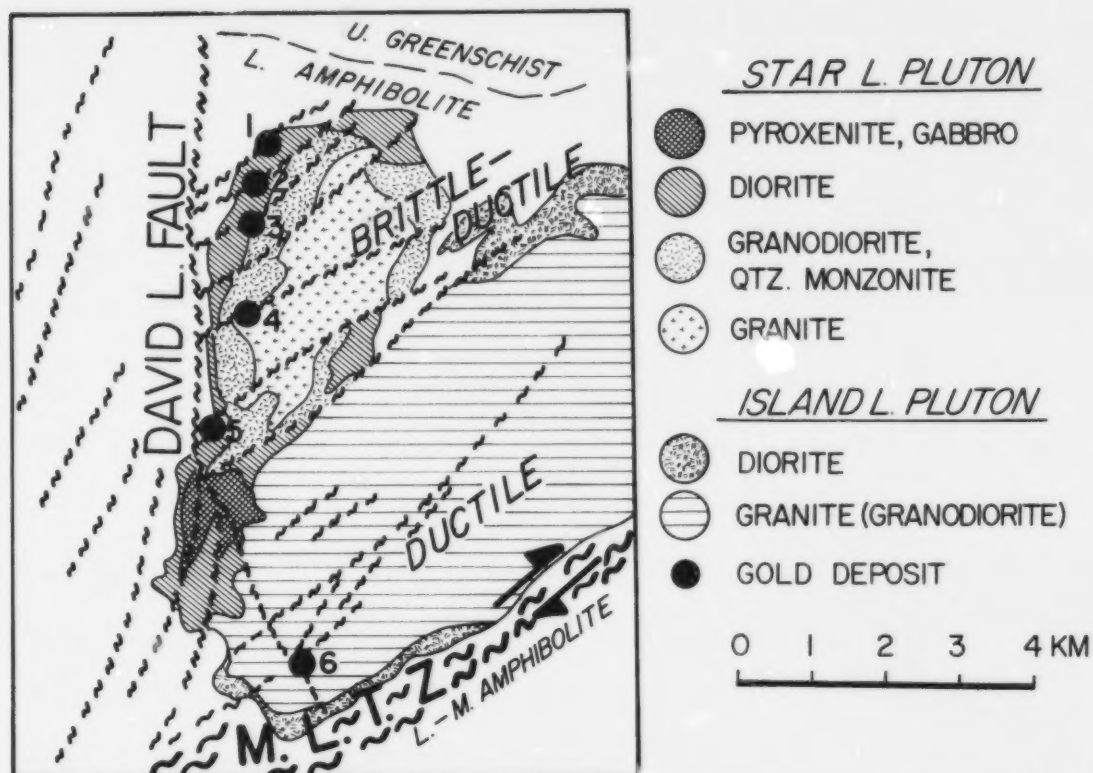


Figure 8 - General geology of the Star Lake area. Numbers refer to shear zone-hosted gold deposits: 1) Jolu (Decade Mine); 2) Rod Zone; 3) Rush; 4) 21 Zone, Kahn 18; 5) Tamar; 6) Jasper - James. MLTZ = McLennan Lake Tectonic Zone.

faults and cut by later quartz veins. Both tension, and the dominant shear veins, display a 'crack - seal' laminated or banded texture, ranging from millimetre-scale mica and/or chlorite ribbons up to centimetre thick slabs of wallrock material interlayered with the quartz. Multiple sets of P and D shear veins commonly coalesce to form thick massive 'trunks' within the vein system. Ongoing deformation during vein development is indicated by the presence of older brecciated, rotated, boudinaged and folded veins which are cut by progressively younger veins. Towards the margins and ends of the vein system, individual quartz lenses are commonly sheared forming thin mylonitized quartz ribbons. Therefore, a single quartz vein system can display a spectrum of variably deformed veins along with apparently undeformed veins, all of which were emplaced during a single progressive shearing event.

7. Majority of mineralized vein systems lack a pronounced wallrock alteration. Macroscopic wallrock alteration is generally absent to only weakly developed around most of the shear zone hosted deposits. Patchy tourmaline and narrow potassium alteration zones, defined by biotite or sericite occur ad-

jacent to some vein systems (e.g. Rod zone, Seabee deposit). In dioritic wallrocks adjacent to the Mallard and Rod zones, an irregular to patchy tourmalinization halo is characterized by finely disseminated needles or locally by coarse tourmaline pods that tend to increase in size (up to 10 cm diameter) towards the veins. The pods, which occur within a few metres of the veins, are themselves enveloped by a centimetre thick mantle of mafic-depleted or 'bleached' diorite. Thin biotite seams are commonly developed at the contact between the quartz veins and dioritic wallrocks.

A pale green sericitization halo, up to a few metres wide, is the most noticeable alteration distinguished around granitic-hosted veins (eg. Blindman, 21, and Kahn 18 zones). A weak potassium alteration, defined by biotitic seams and K-feldspar porphyroblasts, is locally developed within many of the sheared mafic to felsic dykes and unmineralized quartz veins throughout the central part of the Star Lake Pluton.

Notable exceptions to this tendency are the Weedy Lake A and B zones, which possess broad alteration

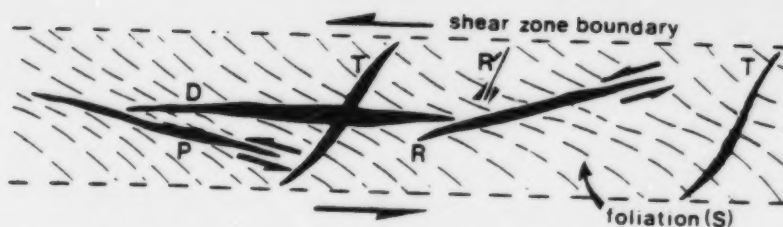


Figure 9 - Orientation of shear fractures and extension fractures in brittle - ductile shear zones (from Roberts, 1987).

haloes (at least 5 m) around the vein systems. Potassic alteration is indicated by biotite replacing hornblende in the dioritic hosts. Other types of alteration include chloritization, carbonatization, pyritization and silicification (Harper, 1984).

Deposits hosted by structures characterized by a more brittle style of deformation (e.g. Tower Lake East, Jojay and Komis deposits) tend to have a more pronounced wallrock alteration which includes carbonate, finely disseminated pyrite, biotite, sericite, tourmaline, epidote and hematite.

8. Positive correlation between gold distribution and sulphide-rich portion of quartz veins. Gold mineralization occurs in veins composed predominantly of quartz with subordinate amounts of chlorite, biotite, epidote, tourmaline, pyrite and pyrrhotite. Minor to trace amounts of molybdenite, chalcopyrite, bornite, covellite, galena, sphalerite, arsenopyrite, tetrahedrite and scheelite have been reported from one or more of the deposits in the Star Lake and Waddy - Tower Lakes areas. Gold is generally present as the native metal in these deposits with grades typically displaying a positive correlation with the pyrite and/or pyrrhotite content in the veins; and at Seabee with chalcopyrite as well (Delaney, pers. comm.). Gold occurs along microfractures in the sulphides and to a lesser degree along fractures in the quartz. Various telluride minerals have been identified in association with gold in the 21 zone and Seabee deposits. Varieties at the 21 zone include calaverite (AuTe_2), tellurobismuthite (Bi_2Te_3), hessite (Ag_2Te) (Poulsen *et al.*, 1986). At Seabee bismuth, nickel, iron and rare gold tellurides are reported (Delaney, pers. comm.).

Sulphide development is typically patchy or irregular throughout the veins; however, there is a general tendency for increased Fe sulphide concentration along the margin of wallrock fragments incorporated in the quartz veins. Sulphides include very coarse euhedral pyrite cubes (e.g. 21 zone), framboidal pyrite aggregates (e.g. Jolu occurrence), very finely disseminated

pyrite 'dusting' (e.g. Jasper Pond) and coarse massive pyrrhotite (e.g. Rod Zone).

At the Komis deposit, near Waddy Lake, pyrite cubes form distinct haloes adjacent to the quartz veins and are less abundant in the veins. Size and percentage of the cubes decrease away from the

veins. In this deposit gold values are typically greater in the pyritized wall rocks than in the quartz veins.

In the Star Lake area, a very rudimentary sulphide zonation can be distinguished between the various deposits. The northern deposits (e.g. Mallard and Rod zones) contain approximately equal amounts of pyrite and pyrrhotite with minor chalcopyrite and molybdenite; this gives way to increasingly pyrite-dominated veins southwards. Pyrrhotite appears to be essentially absent from vein systems developed within the central part of the Star Lake Pluton. The most complex vein mineralogy appears to be in the more southerly deposits (e.g. Jasper - James zone), where the pyrite-dominated gangue suite is associated with galena, sphalerite, tetrahedrite, chalcopyrite, bornite and covellite. The southwards increase in pyrite:pyrrhotite ratios in the vein systems may be due in part to the reaction of the mineralizing fluids with wallrocks of different compositions.

Deposits in the northern part are hosted by dioritic rocks of the Star Lake Pluton while the more southerly deposits are hosted by granitic to quartz monzonitic rocks of the Star Lake and Island Lake Plutons. Alternatively, the difference in gangue mineralogy may reflect differing physiochemical conditions during deposition of the various vein systems.

CONCLUSIONS

On the basis of regional- and deposit-scale investigations of structurally-controlled gold mineralization in the La Ronge Gold Belt a number of empirical characteristics common to the majority of deposits have been briefly outlined. In summary, they included:

- i) A strong spatial distribution to greenstone-plutonic belts, particularly areas that attained upper greenschist to lower amphibolite metamorphism.
- ii) Intrusive rocks provide the most favourable rheological environment for the development of suitable structural sites for vein systems.

- iii) Deposits are hosted by lower order structures related to major regional faults or shear structures. Deposits are situated in zones of extension developed during periods of dominantly horizontal movement along the regional-scale structures.
- iv) Majority of mineralized shear structures reflect the brittle - ductile transition regime, although deposits in brittle and ductile settings also exist. Structural or compositional irregularities along the structures are areas for major quartz vein development.
- v) Vein systems hosted by brittle - ductile shears generally exhibit weak to negligible wallrock alteration. Deposits developed in more brittle structural settings tend to possess a more pronounced wallrock alteration.
- vi) Gold displays a positive correlation in most deposits with the sulphide distribution in the quartz veins or adjacent wall rocks.

The majority of greenstone belt gold camps in Canada are in the Archean of Ontario and Quebec. A result of this apparent temporal distribution of major lode gold deposits to Archean greenstone belts is a general precept that gold deposits in Proterozoic belts are much less significant (Hutchinson, 1987). The prevalence of major gold deposits in Archean greenstone belts as compared to Proterozoic belts has been explained by some workers as a function of bulk compositional differences between Archean and early Proterozoic rocks and seawater, and the effects of early Proterozoic oxygenation of the atmosphere-hydrosphere on the mobilization and transport of gold (Hutchinson, 1987). Alternatively, the historic success of exploration in the Archean belts of eastern Canada may reflect their volumetric predominance over similar belts of early Proterozoic age as well as their geographic location, but not necessarily that they have an inherently greater gold concentration per kilometre³. The physical characteristics of the lode gold deposits of the La Ronge Gold Belt are essentially the same as their Archean counterparts. Therefore if the processes which form lode gold deposits were fundamentally the same in both the Archean and Early Proterozoic, then the exploration potential of the latter should be equally as good.

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STRUCTURAL CONCEPTS FOR GOLD EXPLORATION: BRIDGING THE GAP BETWEEN THEORY AND PRACTICE

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ABSTRACT

As a result of the high level of gold exploration in the 1980's, economic geologists have once again focussed their attention on the numerous technical problems that relate to the geology of gold deposits. Much of the research on these topics has been devoted to the establishment and testing of genetic models that are used to guide exploration in a general way, but, in practice, there is a greater requirement for specific concepts and methods that can be applied routinely to optimize exploration programs. In all topics that pertain to the geology of gold deposits, there is commonly a large gap between theoretical concepts and their practical application, and structural analysis applied to gold exploration is no exception.

The productive gold deposits of the Archean and Proterozoic granite-greenstone terranes of the Canadian Shield, as typified by the La Ronge Domain in Saskatchewan, show an uncanny correlation with shear zones, and to a lesser extent with folds. Most genetic controversies centre on the significance of such a relationship, be it fortuitous or causative. Regardless of genetic implications, this relationship has broad application in exploration because such structures commonly dictate not only the sites for gold concentration, but also the orientation of individual veins and shoots. Most productive gold deposits comprise several orebodies of complex shape and arrangement but typically are constructed from one or more simpler elements such as shear veins (veins parallel to, and within, shear zones), extensional veins, and vein breccias that typically involve oblique extension. Where sufficient data have been collected, it appears that the orientations of these elements are not random but are related to definable deposit-scale axes of extension and shortening that, in turn, are coincident with regional fabric axes that are inferred from observation of lineation and foliation in the vicinity of deposits. Plunges of ore shoots are commonly coincident with one or more of these axes.

Although the theoretical basis for structural analysis is firmly established, there are many limiting factors such as lithological anisotropy that prevent such analysis from being treated as an exact science for the purpose of gold exploration but, treated with caution, it can be used as a technique to optimize exploration programs.

THE BAKOS DEPOSIT DISCOVERY - A CASE HISTORY

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ABSTRACT

The Bakos deposit is located within the La Ronge Gold Belt, approximately 45 km northeast of La Ronge, Saskatchewan. It was delineated in 1989 during two drill programs comprising 113 holes totalling 18,057 m. The in situ reserve as of December, 1989, was estimated at 1.15 million tonnes grading 9.9 g/t (1,270,000 tons grading 0.29 oz/ton) Au. The reserve is contained in a zone 600 m long, extending to vertical depths ranging from 180 to 280 m. The deposit remains open along strike and down dip.

The Bakos deposit occurs within a poorly exposed regional northeast-striking shear zone which cuts granitic and granodioritic phases of the Little Deer Lake Pluton. Segments of the structural zone are pyritized, sericitized and locally hematized. The gold is typically present in altered rocks adjacent to the structural hanging wall. Mineralized intervals from 1.5 to 15 m wide contain up to 5% quartz and sulphide veinlets. Sulphides present are pyrite > > chalcopyrite > pyrrhotite, galena and trace amounts of sphalerite, molybdenite and chalcocite. Visible gold is common and the average Au:Ag ratio for the deposit is 1:1.

The Bakos deposit was discovered largely by geochemistry. In 1984, a lake sediment anomaly was followed up by analyzing heavy mineral concentrates from five widely spaced bulk till samples. Two of the five samples were anomalous. Additional bulk till samples collected during 1985 and 1986 systematically traced the anomaly up-ice for 2.0 km. The regional shear zone was located in 1987 and a 400 m lake-covered segment of the zone was tested by eleven drill holes in 1988. The drilling results were encouraging. Following a summer exploration program, the main deposit was intersected by drill holes in the winter of 1989.

INTRODUCTION

The Bakos deposit is located in the La Ronge Gold Belt, approximately 45 km northeast of La Ronge, Saskatchewan (Figure 1) on land held by the Preview Lake Joint Venture, which comprises Cameco (50%), Uranerz Exploration and Mining Limited (30%) and Westward Exploration Ltd. (20%). Cameco is the project operator.

The deposit occurs within a poorly exposed regional shear zone which cuts granite and granodiorite phases of the Little Deer Lake Pluton. It was discovered largely by geochemistry. In 1984, a lake sediment anomaly was evaluated by gold grain counts of heavy mineral concentrates from bulk till samples.

Two of the five, originally widely-spaced samples were anomalous and additional bulk till sampling in 1985 and 1986 systematically traced the anomaly up-ice for 2.0 km. The shear zone was located by prospecting at the head of the bulk till train in 1987. A 400 m lake-covered segment of the zone was tested by eleven drill holes in 1988, with encouraging results and following a summer exploration program, the main mineralized zones of the deposit were intersected in the winter of 1989.

The deposit, delineated in 1989 by two drill programs comprising 113 holes totalling 18,057 m, contains *in situ* reserves, as of December, 1989, estimated at 1.15 million tonnes grading 9.9 g/t

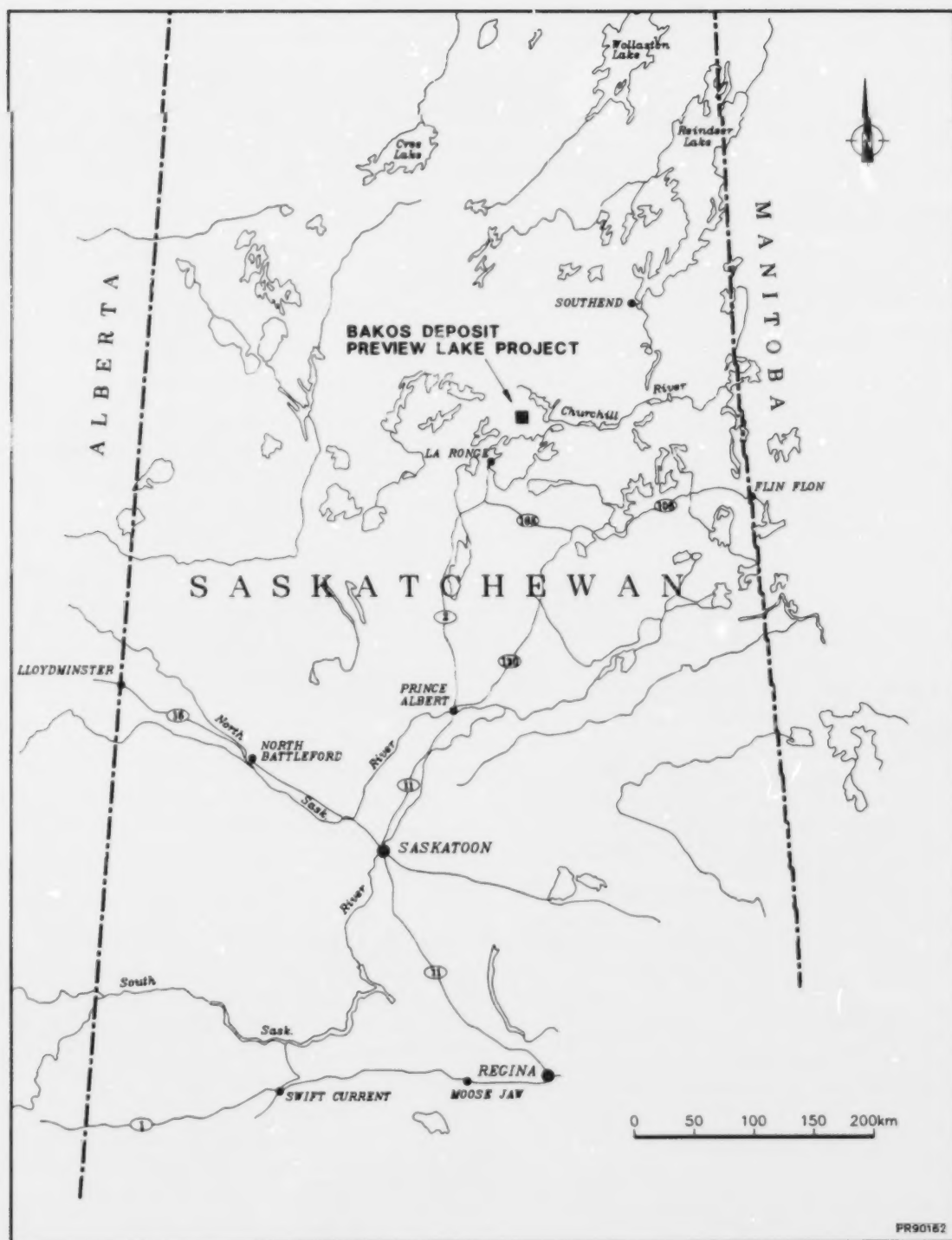


Figure 1 - Location map of the Bakos deposit and Preview Lake Project.

(1,270,000 tons grading 0.29 oz/ton) Au. The reserve is contained in a zone 600 m long, extending to vertical depths ranging from 180 to 280 m.

REGIONAL GEOLOGY

The Bakos deposit is located within the Little Deer Lake Pluton, which outcrops near the junction of four lithostructural belts (Lewry, 1984) forming the southern portion of the Aphebian La Ronge Domain in northern Saskatchewan (Figures 2 and 3). To the west of the pluton is the northwest-trending Crew Lake Belt; to the north are the north-trending Central Metavolcanic and the MacLean Lake Belts; and to the south and east is the northeast-trending Nut Bay Belt. A discussion on the regional geology can be found in Forsythe (1968), Lewry (1984), Thomas (1986 and 1987) and Slimmon (1986). Results from currently published geology are summarized below.

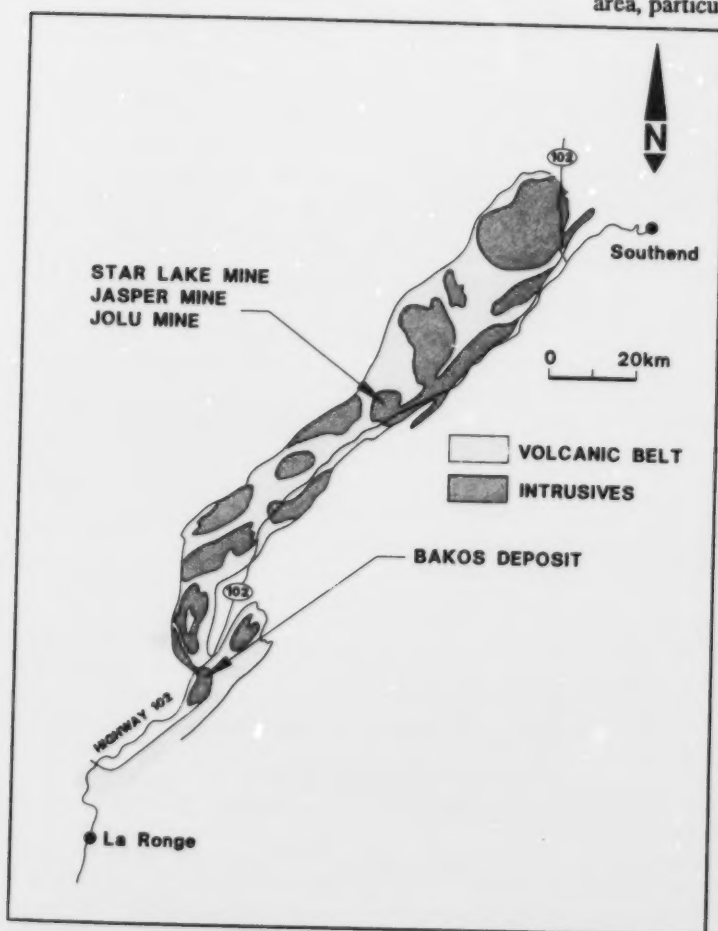


Figure 2 - Intrusives and gold mines of the Central Metavolcanic Belt, La Ronge Domain.

The Crew Lake Belt consists of a monotonous sequence of psammitic to psammopelitic and minor pelitic rocks of probable turbidite affinity. This belt grades into the Central Metavolcanic Belt comprising relatively undeformed, mafic to intermediate flows and volcanoclastics, and subordinate felsic volcanic rocks. Volcanoclastic and other volcanogenic sedimentary rocks form a progressively larger portion of this belt farther south. The MacLean Lake Belt, to the east, appears to be laterally transitional, and stratigraphically equivalent to, the Central Metavolcanic Belt; however, locally the latter appears to be thrust over the former. The MacLean Lake Belt comprises psammitic to pelitic rocks, calc-silicate gneisses, amphibolites and polymictic conglomerates. Both the Central Metavolcanic Belt and the MacLean Lake Belt appear to be unconformably overlain by a thick sequence of arkoses and arkosic conglomerates belonging to the McLennan Group. The unconformity is not well defined in the northern area, particularly where the western contact of the

McLennan Group abuts the highly strained rocks of the McLennan Lake Tectonic Zone.

Large rounded to ovoid plutons are found throughout the Crew Lake and Central Metavolcanic Belts. They are typically massive to moderately foliated composite intrusives with diorite to granodiorite margins and monzonite to granite cores. The MacLean Lake Belt and the McLennan Group generally contain later intrusives occurring as small plug- or sill-like bodies of massive to weakly foliated leucogranite.

Further east, the Nut Bay Belt comprises a linear belt of strongly foliated and relatively homogeneous granite to granodiorite gneisses with subordinate supracrustals. The supracrustal rocks adjacent to the transition zone with the other belts consist of a thick sequence of dominantly felsic to intermediate volcanoclastics with subordinate pelitic sediments.

An interpretation consistent with the available geological and geochemical data, as summarized from Thomas (1987) and Watters (1986), supports a sedimentary basin (Crew Lake Belt) transitional into island arc-style volcanism (Central Metavolcanic Belt) with the concurrent development of a greywacke basin (MacLean Lake

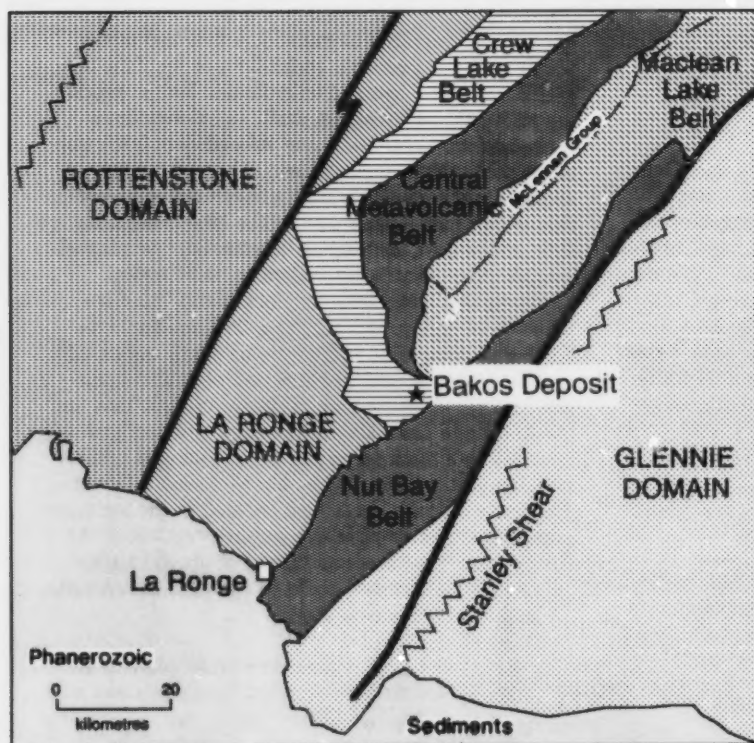


Figure 3 - Major lithostructural elements of the La Ronge area, modified from Lewry (1984).

Belt). Volcanic assemblages in the Sulphide Lake area of the Nut Bay Belt may be a dismembered extension of the Central Metavolcanic Belt.

Geochronological data from the Central Metavolcanic Belt, summarized from Thomas (1987), supports Lower Proterozoic (ca. 1880 Ma) island arc volcanism followed by major plutonism between 1870 and 1830 Ma ago. Peak regional metamorphism occurred between 1840 and 1780 Ma ago (Bickford *et al.*, 1990).

Most of the southern La Ronge Domain has attained lower to middle amphibolite conditions of regional metamorphism. This area is also structurally complex with most supracrustal rocks showing evidence of at least two deformation events.

LOCAL GEOLOGY

The Little Deer Lake Pluton occupies an area of 8 km by 6 km (Figure 4). It is a fairly irregular-shaped body that exhibits typical intrusive contacts with the surrounding supracrustal sequences. This composite pluton varies from gabbro and diorite near its outer margins to granodiorite and granite at its core. The internal contacts between the intrusive phases are

commonly gradational, however, intrusion breccias and sharp interfingering contacts occur locally. Field relationships indicate that the mafic phases are oldest and have been intruded by multiple pulses of progressively more felsic magma.

The intrusive rocks are typically fine to medium grained and massive. Locally, a weak metamorphic foliation is developed parallel to the margins of the intrusion.

Three major northeast-trending structural zones have been mapped in the area. The PAP - Preview Lake shear system is located to the east of the Little Deer Lake Pluton. It comprises a wide, high strain zone that manifests itself as broad zones of intense foliation in felsic volcanic rocks and as numerous narrow, closely-spaced shear zones in diorite and gabbro intrusives/sills. Numerous gold showings occur within the sheared intrusives, including the PAP SW deposit. The Curry Zone is a 150 m wide zone of intense shearing localized along a granodiorite/quartz diorite contact trending through the middle of Contact Lake. No gold showings of significance have been located along this structure to-date. The third zone, the Bakos Zone, hosts the Bakos deposit.

REGIONAL EXPLORATION HISTORY

Gold exploration in the southern La Ronge Belt dates back to the 1930's and 1940's when a number of gold occurrences were located and evaluated in the general Contact Lake area. Small gold deposits were delineated at Sulphide Lake and Preview Lake. During the 1950's and 1960's, exploration took place largely around known deposits, primarily in the supracrustal sequences enveloping the Little Deer Lake Pluton. By 1978, there were approximately 30 known gold showings in the general Sulphide-Contact- Preview Lakes area.

In 1978, Saskatchewan Mining and Development Corporation (SMDC) initiated a regional exploration program to evaluate the gold and base metal potential in this portion of the belt. The program consisted of INPUT surveys, lake sediment sampling and geological mapping. Prospective target areas were

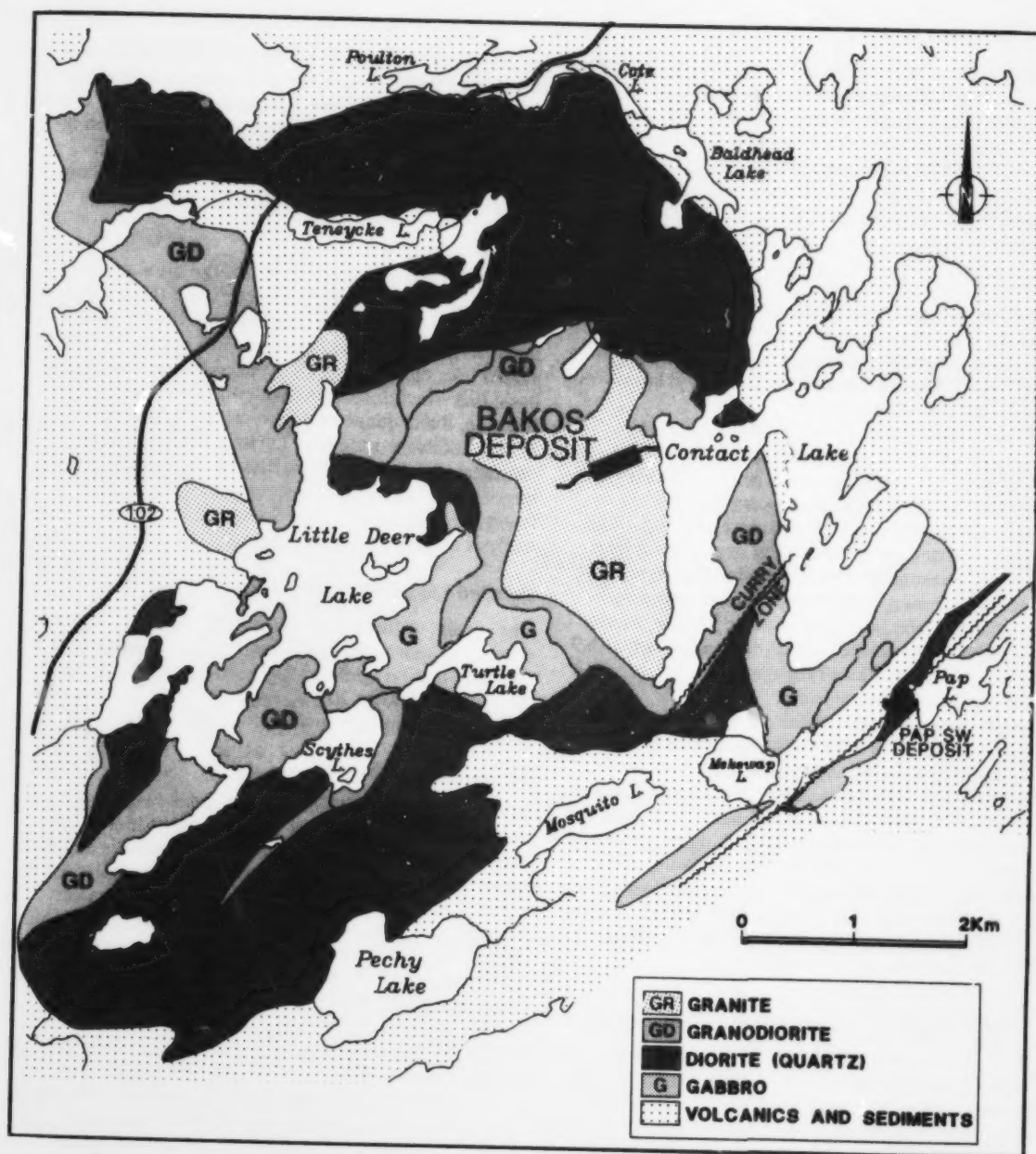


Figure 4 - Geology of the Little Deer Lake Pluton.

identified and much of the current land holdings were acquired. During 1979 and 1980, first order targets were evaluated. Dispositions within the La Ronge Provincial Park were closed to exploration from 1981 to 1983. When activity resumed in 1984, it concentrated on the areas around the historic gold showings and a gold deposit was outlined at PAP Lake by drilling in 1986, 1987 and 1988. An underground test entry was planned for this deposit in 1989, however, it is still awaiting regulatory approval.

BAKOS DEPOSIT - DISCOVERY OVERVIEW

Introduction

The discovery of the Bakos deposit can be traced back to 1978 when a gold-in-lake sediment survey carried out by SMDC identified a 30 ppb gold anomaly in Turtle Lake. In 1984 a small field program was initiated to evaluate the high anomalous values in Turtle Lake and nearby Mosquito Lake after the

anomalies were first confirmed by additional sampling. In addition to prospecting and mapping, biogeochemical samples were collected over a flagged grid and five bulk till samples (5 - 7 kg) were collected from widely separated areas around Turtle Lake. Two of the five bulk till samples contained anomalous numbers of gold grains in their heavy mineral concentrates.

Field programs completed during 1985 and 1986 systematically traced the bulk till anomaly for 2.0 km up-ice to the shores of Contact Lake. The anomaly was eventually closed off to the north and east by background gold values. The area to the west is largely unsuitable for sampling.

A regional shear zone was located in 1987 while prospecting and mapping at the head of the bulk till gold anomaly. The shear zone occurs in a topographic low between two granite outcrops. The hanging wall and the gold deposit are covered by 5 to 8 m of overburden. The footwall locally outcrops along the base of a steep scarp. Numerous narrow and discontinuous quartz veins were located within the massive footwall rocks and returned values of 6.9 to 113.2 g/t (0.2 to 3.3 oz/ton) Au.

A 400 m lake-covered segment of the shear zone was first drilled tested in 1988 in the vicinity of the interpreted source area for the gold-in-till anomaly. The drilling results were encouraging, but inconclusive due to the irregular nature of the auriferous quartz and sulphide veinlets. A second drilling program was initiated during the winter of 1989 following an IP-Resistivity survey and a sonic overburden drilling program. Significant gold mineralization was intersected by the initial holes and the Bakos deposit was subsequently delineated.

Geochemical Exploration Techniques

One of the first attractions to the area, in 1984, resulted from a review of gold in lake sediment data. The initial lake sediment survey was conducted by SMDC in 1978 and the subsequent publication (Coker *et al.*; 1980) represented the first published account of the use of lake sediments in gold exploration. Several lakes around the Little Deer Lake Pluton were anomalous including Turtle Lake at 30 ppb gold. In 1984, additional lake sediments were taken to confirm the earlier results and fill in any gaps in the coverage. The anomalous nature of Turtle Lake was confirmed by three samples which analyzed 15, 20, and 21 ppb gold, although values were lower than for the initial 1978 survey as a result of using a different analytical technique. The 1978 survey utilized fire assay-neutron activation, whereas the 1984 survey employed low temperature ashing followed by graphite furnace-atomic absorption. The

greater than 10 ppb gold contour outlined an area around the Little Deer Lake Pluton and encompassed most of the known gold showings (Figure 5). Only those samples with greater than 10% loss on ignition are shown in Figure 5, as organic-rich sediments from lake centres were found to be more consistent in their gold contents than low organic samples.

Following the lake sediment work, the area around Turtle Lake was examined to determine the best approach to exploration. It was found to lie, for the most part, above the regional level of deposition of glacial lake clays and to be covered by locally derived basal tills which form a semi-continuous blanket over the area. Subsequent geochemical work included: 1) lake sediment survey of Turtle Lake, 2) biogeochemical survey around Turtle Lake, 3) collection of large basal till samples for gold grain counting in heavy mineral concentrates and 4) fine fraction analysis of bulk till and soil samples.

Detailed Lake Sediment Survey, Turtle Lake

The results of the detailed lake sediment survey are shown in Figure 6. Organic-rich center lake samples (18-22% loss on ignition) consistently yielded greater than 10 ppb (range 10 - 22 ppb) gold. Near-shore organic-poor samples showed lower gold values.

Biogeochemical Survey

In the spring of 1984, humus and alder twigs were sampled on a grid around Turtle Lake. Alder samples were collected every 50 m along lines 100 m apart over an area of 2 km². However the analytical results proved somewhat unimpressive in terms of the pattern of anomalous responses. Gold in the ash of 400 alder twigs showed a geometric mean of 2.7 ppb (range 0.4 - 80 ppb) and only the last line of alder samples, 150 m northeast of Turtle Lake, showed elevated gold values of 2 - 7X background (range 6 - 23 ppb) over an interval of 300 m. Follow-up prospecting did not locate gold showings. As a result, alder sampling was discontinued. This line of anomalous alders, in hindsight, did correspond to an area of anomalous gold grains in till (50-100 grains in 6 kg) and the start of what was to become a major gold-in-till train.

Bulk Till Survey

The area is well suited for the collection of basal tills. Work by J. Campbell (1987) indicated that a lower grey till, probably related to the most common ice direction of 212° to 218° and containing pebbles generally of local derivation, was the preferred sampling unit. An upper till in which pebble lithologies appear to be far-travelled is also present. Impedi-

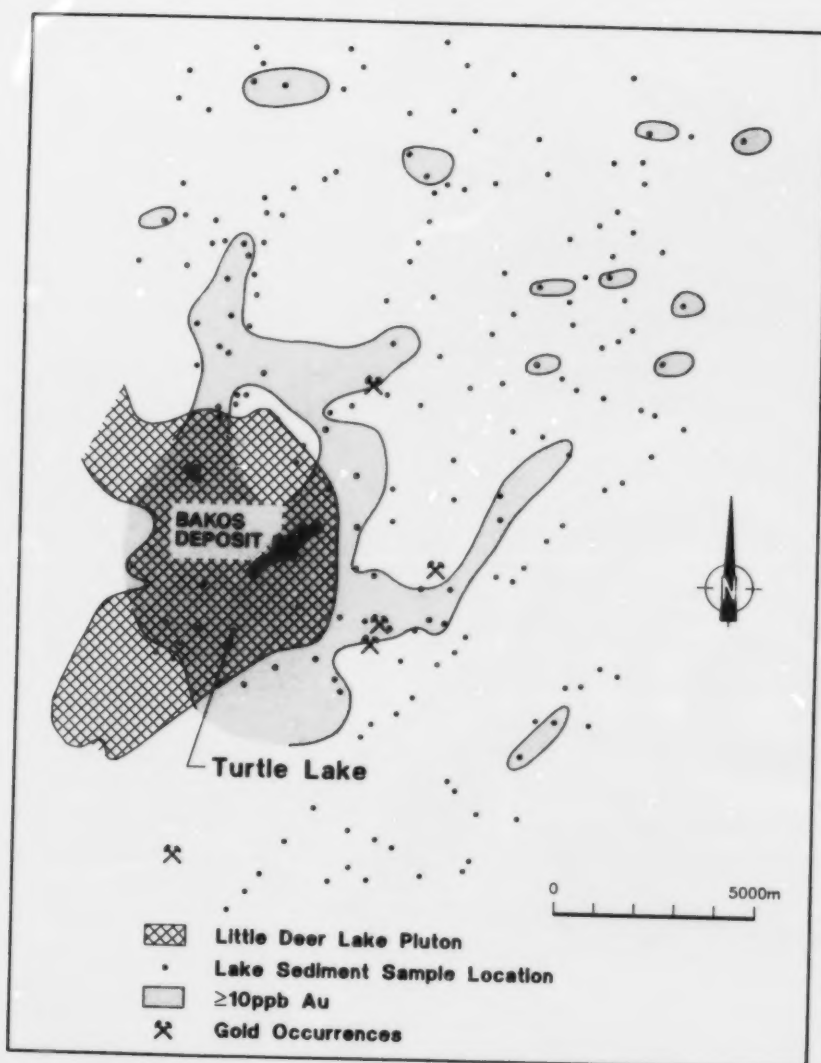


Figure 5 - Gold (ppb) in lake sediments, Preview Lake project area.

ments to the collection of the lower till are glaciolacustrine and upper till deposits.

Five bulk till samples were collected at widely spaced points around Turtle Lake during the summer of 1984 (Figure 7). Normalized values of 81 and 72 gold grains were obtained from two sample sites along the south shore of the lake and were considered elevated for areas underlain by intrusive rocks. A description of sample collection and processing for these early samples is given in Sopuck *et al.* (1986).

Up-ice prospecting and collection of additional bulk till samples was undertaken in the summer of 1985 and 1986 and sampling over Contact Lake was under-

taken in the winter of 1989 by a lightweight track mounted mini-sonic rig (Figures 8 and 9). In total, approximately 125 samples were collected. A highly anomalous gold-in-till train measuring 2 km long and 500 m wide was traced to the shores of Contact Lake in 1986. Gold grain counts ranged from the original 81 grains found in a sample at Turtle Lake, to 200 grains 1 km up-ice, to 2751 grains near the west shore of Contact lake. Gold values obtained by fire assay of the heavy mineral concentrates ranged from 20 g/t at Turtle Lake to 240 g/t near Contact Lake. A sharp cut-off in gold grain values occurred in the area of the yet to be discovered Bakos Structural Zone. Gold grain counts drop from 200-2000 grains south of the structure to 25 grains in several samples taken to the north of it.

Very sandy ablation tills in an area of outcrop ridges south of the Bakos Structural Zone contained a high proportion of exotic material and lower gold grain counts. These ablation tills explain the hole in the gold dispersion train (Figure 8).

In conjunction with bulk till sampling and processing, the pebble lithologies of the anomalous tills were examined in the laboratory and in the field. Pits dug into basal tills near Contact Lake (Figure 10) showed a majority of angular felsic intrusive fragments. Immediately south of the Bakos Structural Zone they comprised approximately 90% by volume, of the -1 cm fraction. Volcanic and sedimentary material formed 4% and sheared pyritic intrusives and limonitic quartz comprise the remaining 5%. One year before outcrop expressions of the Bakos Structural Zone were found, the prediction was made for the gold source to be auriferous quartz veins within sheared felsic intrusive rocks.

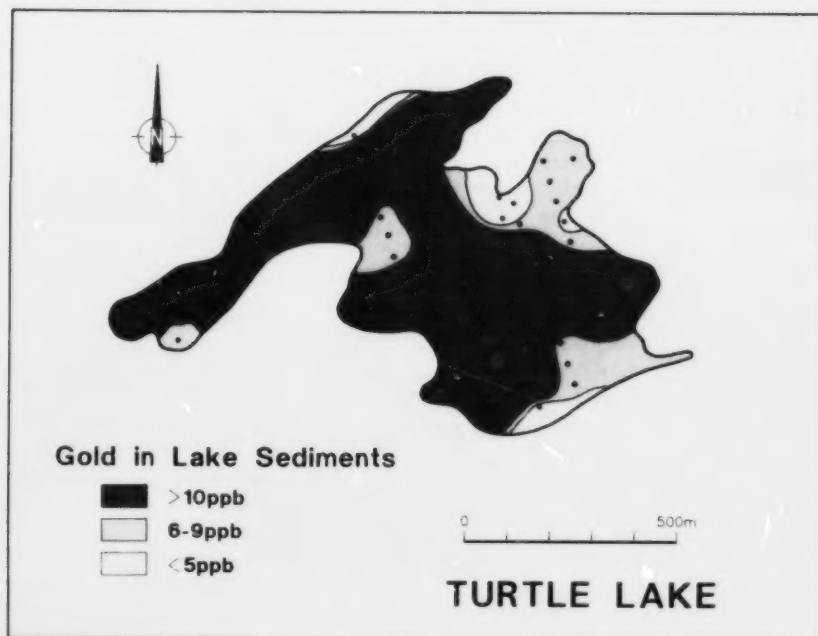


Figure 6 - Gold (ppb) in lake sediments, Turtle Lake.

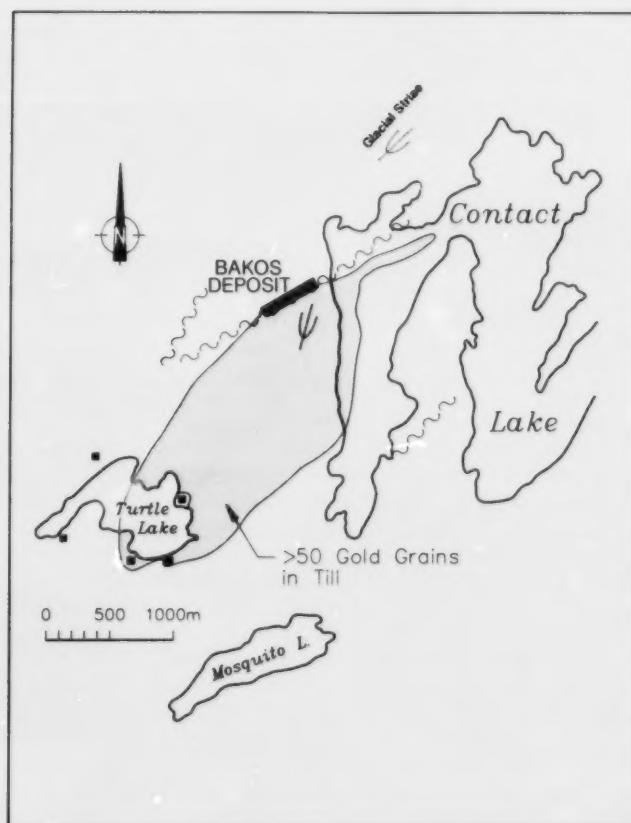


Figure 7 - Outline of Contact Lake gold-in-till train with position of first 5 samples (solid squares) taken at Turtle Lake.

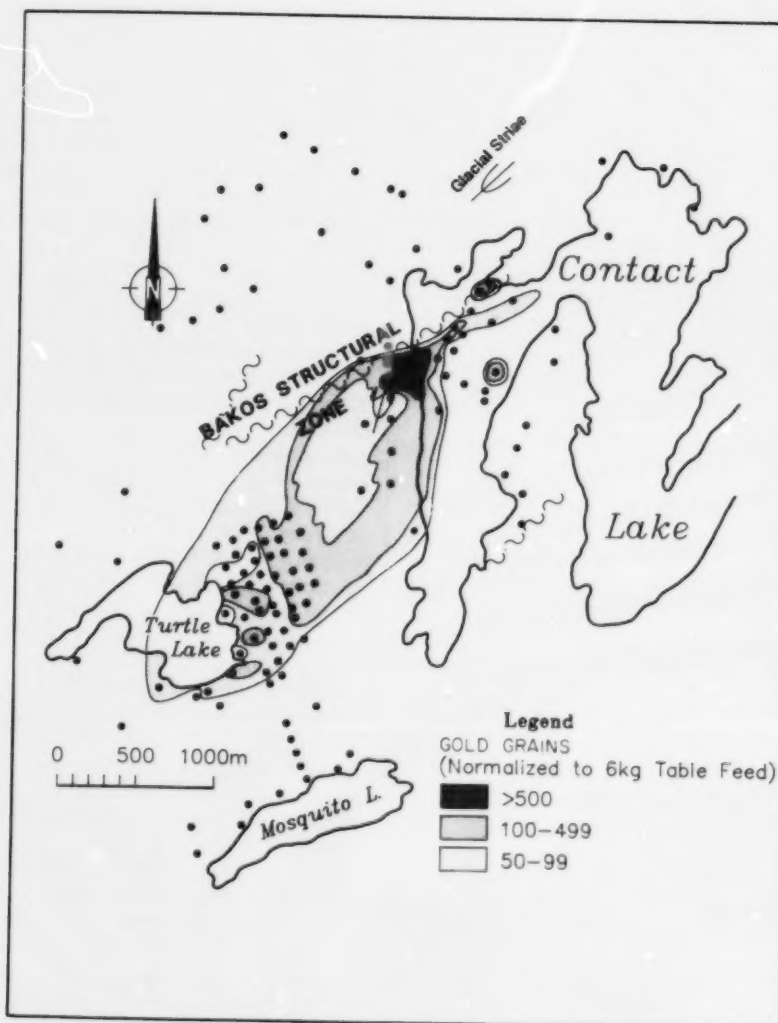


Figure 8 - Gold grains in till, normalized to 6 kg table feed. Solid dots represent sample sites.

Gold morphology did not change appreciably as the source area was approached. Sample TL6T2520 (960 gold grains) at a distance of 150 - 200 m from source contained 31.1% delicate grains, 23.7% irregular grains and 45.2% abraded grains. Sample TL6T2512 (399 grains normalized) at a distance of 1.5 km from source contained 27% delicate grains, 42.7% irregular grains and 30.3% abraded grains. In both cases, the larger grains above 200 microns exhibited irregular morphology.

The gold grain size distribution for three representative samples is shown in Table 1. Most (46.1 to 64.1%) of the total number of gold grains, are between 25 and 50 microns in size. Coarse grains (> 400 microns) occur in several samples through-

out the train and contribute significantly to the heavy mineral assay.

Fine Fraction Analyses and Soil Survey

Sopuck *et al.* (1985) have demonstrated that there is a substantial loss of either fine- or silicate-held gold on the shaker table. As a result, the fine fraction analyses were undertaken in addition to the gold grain counting and heavy mineral assay of the bulk till sample. The minus 0.1 mm fraction (-150 mesh) of the till was wet-sieved for a number of bulk till samples and a 10-30 g portion analyzed by either atomic absorption or fire assay - atomic absorption methods. Gold content was compared to the gold grain counts and the heavy mineral assays of the bulk till samples. Sopuck *et al.* (1986) and Campbell (1987) have suggested that there is only a weak correlation between fine fraction and the heavy mineral analytical data. This same relationship appears also to be true on a regional scale in the Contact Lake - Sulphide Lake - Hebden Lake area. Based on 43 observations in the Contact Lake area, for those samples with gold grain counts less than 200 grains, the correlation (Pearson linear correlation matrix) between the fine fraction and the heavy

mineral assay is poor as is that with the number of gold grains (respectively +0.25 and +0.22). If those samples with greater than 200 gold grains are added to the database, the respective correlations become +0.77 and +0.87. Thus, there is a reasonable correlation as one approaches the gold source, when gold grain counts reach or exceed 150 to 200 grains (i.e. approximately 1.0 km from the source and certainly within 200 m of the deposit).

Given this correlation, a 'soil' sampling program was initiated during the summer of 1987 along the west shore of Contact Lake. Small samples (0.5 - 1 kg) of basal till were to be collected from the deeper levels of the B-soil horizon on a cell grid of 50 m x 100 m.

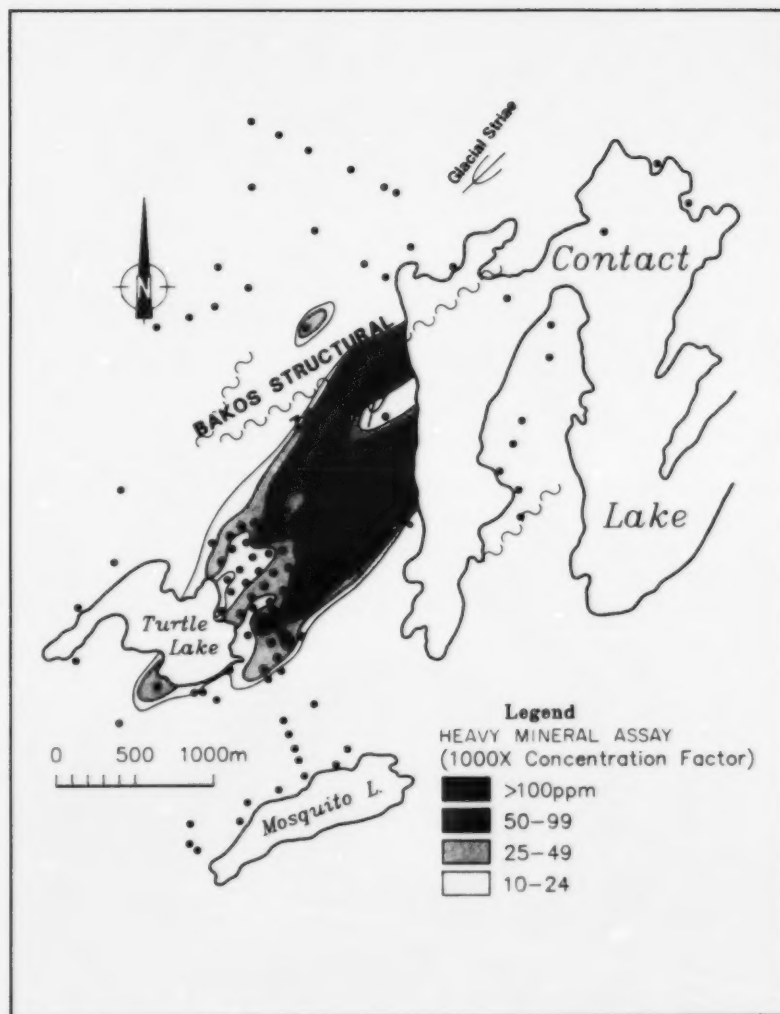


Figure 9 - Heavy mineral assay, normalized to 1000 x concentration. Solid dots represent sample sites.

Table 1 - Gold grain size distribution in three till samples located at 150 m (2520) and 1500 m (2510 and 2511) from presumed source.

Grain Size (microns)	TL6T2520		TL5T2511		TL5T2510	
	no. of gold grains	percent	no. of gold grains	percent	no. of gold grains	percent
25-50	265	46.1	98	54.8	152	64.1
50-100	212	36.9	78	43.5	71	30
100-200	85	14.8	3	1.7	12	5.1
200-300	9	1.6			2	0.8
300-400	2	0.3				
>400	2	0.3				
	575	100	179	100	237	100

Basal tills could not be collected at all sites. Samples consisted of a mixture of basal tills (15 - 20%), Lake Agassiz beach gravels and reworked tills (25%), glaciolacustrine clays and silts (25%), glaciofluvial sands (10%) and ablation tills (20%).

The most anomalous values (> 100 ppb Au) occurred within beach gravels parallel to the west shore of Contact Lake over a distance of 1 km. A large area of ablation till in the middle of the anomalous till train exhibited low gold values (< 20 ppb) in an area where scarce basal tills analyzed > 100 ppb. Thus, without considering the nature of the overburden, the 'soil' survey became difficult to interpret in terms of drill targets. In conclusion, the fine fraction analyses appeared effective close to the gold source, although correct interpretation depends to a large degree on the recognition of the material sampled. If only a 'soil' survey had been completed immediately around Turtle Lake, background values would have been encountered. This case history suggests that bulk till surveys appear to provide a more effective method of quickly evaluating the potential of an area using a coarse sampling cell, which subsequently can direct geologists to the source.

Geophysical Surveys

Ground magnetic, VLF-EM, HLEM and IP-Resistivity surveys have been performed over the shear zone hosting the deposit. The shear zone does not have a distinctive magnetic signature. It correlates, in part, with a subtle VLF response, however, this response was not detected by a follow-up HLEM survey.

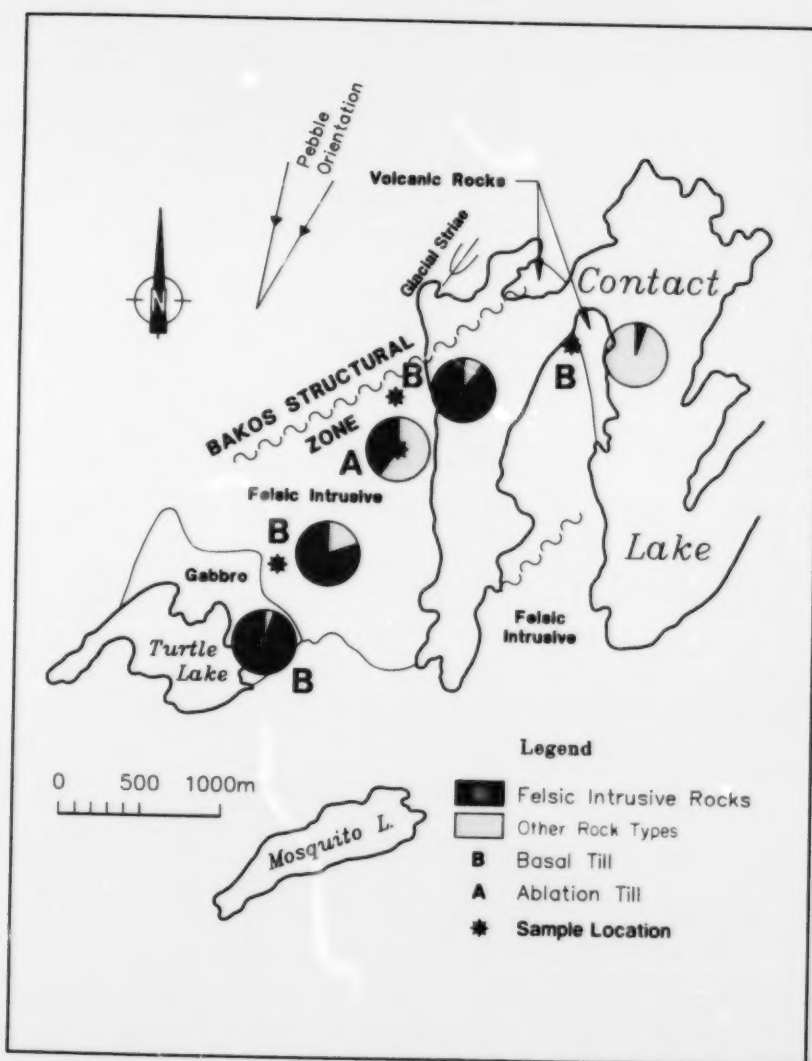


Figure 10 - Pebble counts at selected till sites. The ablation till (A) contained a high proportion of exotic pebbles.

The VLF response is attributed to topography.

The Bakos deposit did respond to the IP-Resistivity surveys. The surveys included gradient array coverage followed by detail dipole-dipole at 25 m stations on selected lines. The deposit coincides with a narrow, distinct chargeability anomaly of 1.5 to 2 times background (Figure 11). This response is likely due to sericitic alteration along shear foliation planes, and to disseminated and stringer pyrite, and possibly sericitic alteration along shear foliation planes.

Geological Mapping and Prospecting

The Contact Lake area has been mapped and prospected since the 1930's. The prominent topographic lineament, now known to host the deposit, has appeared on published geology maps since at least 1968. Several narrow quartz veins located on the footwall ridge, about 50 m from the main deposit, were trenched during the mid-1960's. Despite this knowledge, the difficulties in locating blind deposits using conventional evaluation techniques is well illustrated.

From an exploration perspective, mapping and prospecting would not by themselves have located the Bakos deposit. Both were performed on grid lines concurrently with the geochemical sampling programs. Although several minor shear zones and gold showings were found, results were largely negative. Without the incentive and direction from the geochemical surveys, particularly that resulting from identification of the head of the bulk till anomaly, exploration to follow-up the lake sediment anomaly would have been terminated fairly early. Mapping and prospecting proved invaluable, however, in locating,

tracing and evaluating the shear zone once its potential was recognized.

DEPOSIT GEOLOGY

The Bakos deposit is located within a regional shear zone that transects granitic and granodioritic phases in the core of the Little Deer Lake Pluton. In the vicinity of the deposit, both of these lithologies are fine to medium grained and texturally, are massive to weakly foliated (Plate 1A). The contact between them strikes northerly and dips steeply to the west. The shear zone trends along the base of a high relief bedrock ridge (footwall) which forms a prominent

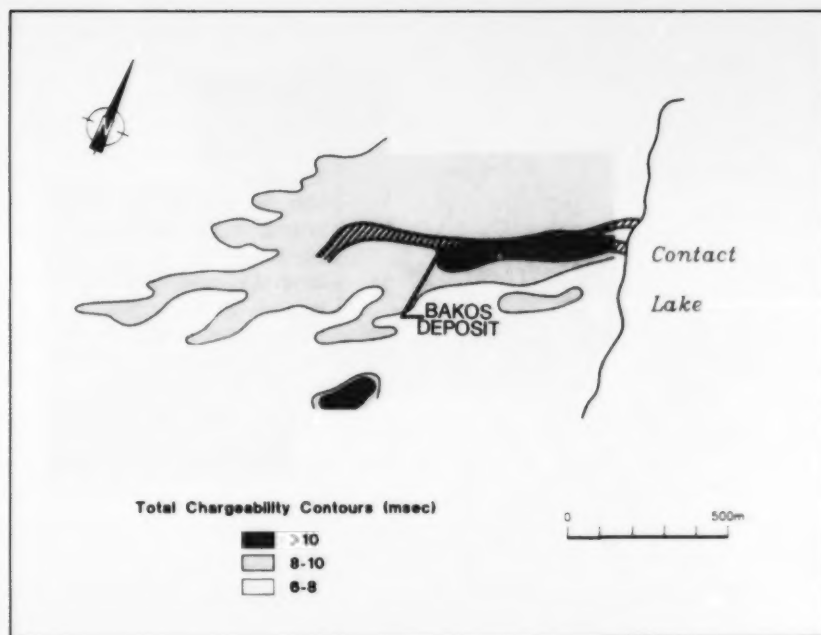


Figure 11 - I.P. - Resistivity survey over Bakos Structural Zone (indicated by the hachured area). The highest chargeability contours correspond to the best mineralized portions.

topographic lineament (Figure 12). The zone is rarely exposed and is generally covered by greater than 5 m of overburden, but drilling confirmed its presence over a 1.4 km strike length, 700 m of which lies beneath Contact Lake. An additional 700 m of strike length is interpreted beneath a linear swamp to the west of the main zone, but this area has not yet been tested by drilling. The shear zone is typically 20 to 30 m in true thickness, trends at 060° to 070° and dips 55° to 65° to the southeast. Within the granite, the shear is a discrete, fairly well defined zone, however, where it crosses the contact into the granodiorite, it splays into several weaker and more diffuse zones.

The limits of the structural zone are defined by the development of a consistent penetrative shear fabric (foliation). The hanging wall contact is typically abrupt, whereas the footwall contact is much more diffuse and appears as a thick zone of moderately foliated rock. Within the structural zone, fabric development is quite variable such that weakly, moderately and intensely foliated intervals alternate (Plates 1 B, 1 C). The more strongly foliated intervals can be correlated both along strike and to depth over distances of more than 200 m. They are commonly best developed in close proximity to the hanging wall contact and in the central portion of the structural zone. Transposed shear foliations within the zone suggest normal dip-slip movement. A broad

amplitude strike-flexure and two low amplitude dip-flexures may be local controls of mineralization.

A late brittle deformation event is manifested in drill core as strongly fractured and locally brecciated portions of the shear zone in close proximity to the hanging wall. The fractured zones have largely been healed by quartz and sulphides. The vein quartz varies from non-strained to highly strained; the sulphides are typically clotted. These brittle features are attributed to a late stage, higher level deformation event, possibly caused by fluid overpressuring.

Alteration

Marked visual alterations within the shear zone comprise sericitization, pyritization and hematization. Sericite occurs in mm- to cm-scale bands along shear foliation planes and is commonly associated with disseminated fine-grained pyrite. Both minerals are typically weakly developed throughout the structure, although, broad alteration envelopes of moderate to intense pervasive sericitization, up to 2% fine-grained pyrite and low gold values [0.7 to 1.7 g/t (0.02 to 0.05 oz/ton) Au] occur around the thicker mineralized shoots.

Hematite forms a fairly widespread, dusty coating on feldspar crystals giving the rock a red brown coloration. Intervals of intense, pervasive hematization occur in weakly to moderately fractured zones adjacent to the main mineralized shoot - generally above a vertical depth of 175 m. The hematite overprints the sericitic alteration and it is likely related to the late brittle fault zones.

Chloritization and silicification occur only locally and do not have a systematic distribution within the shear zone. Quartz veining, however, is more abundant in several of the deepest holes and there may be a vertical zonation of silica enrichment.

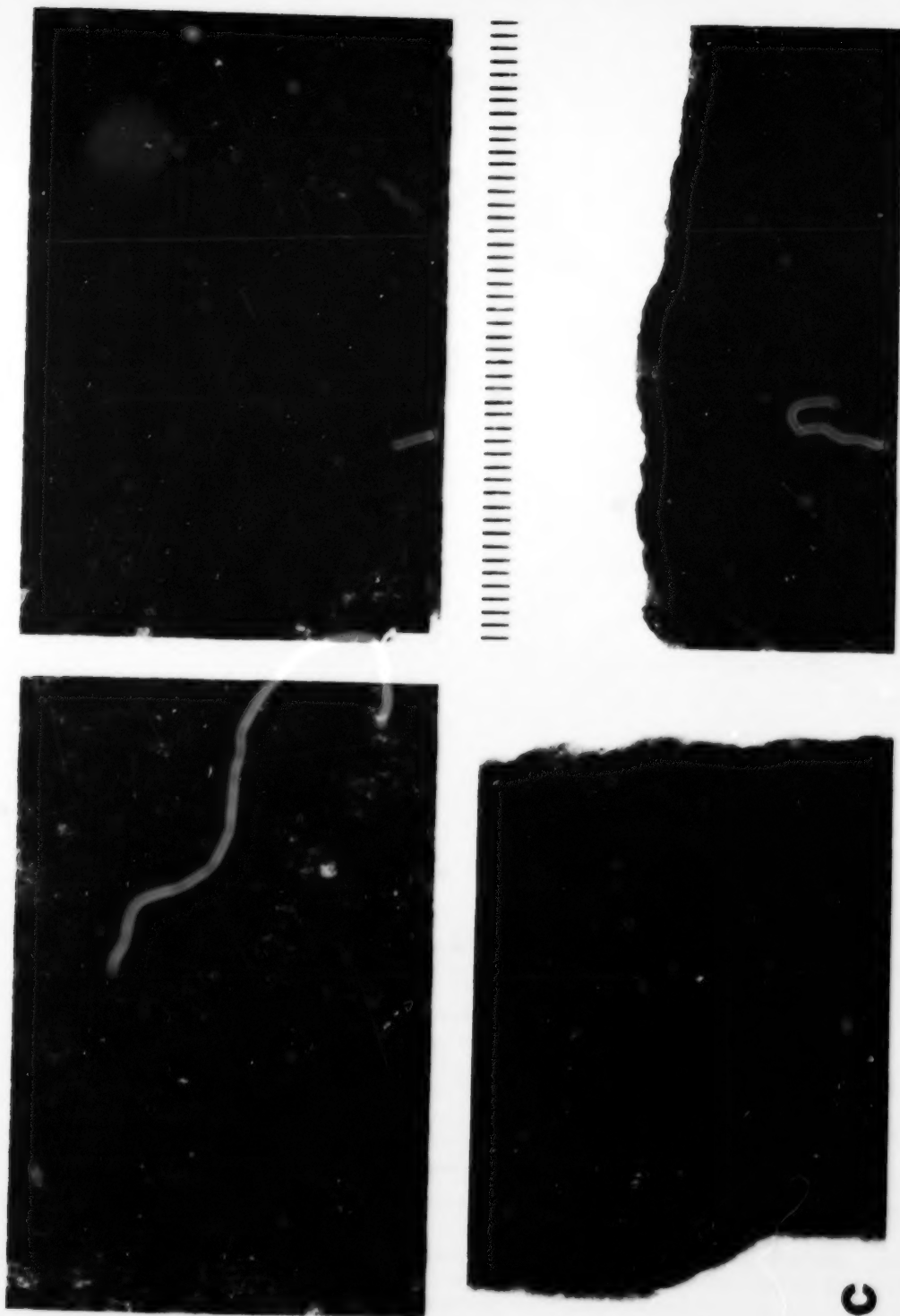


Plate 1 - Structural changes across the Balos Structural Zone: A) massive unaltered granite; B) weakly sheared granite; C) intensely sheared, altered (sericite) intrusive; D) mineralized muscovite-pyrite-quartz vein with remnants of altered wall rock.

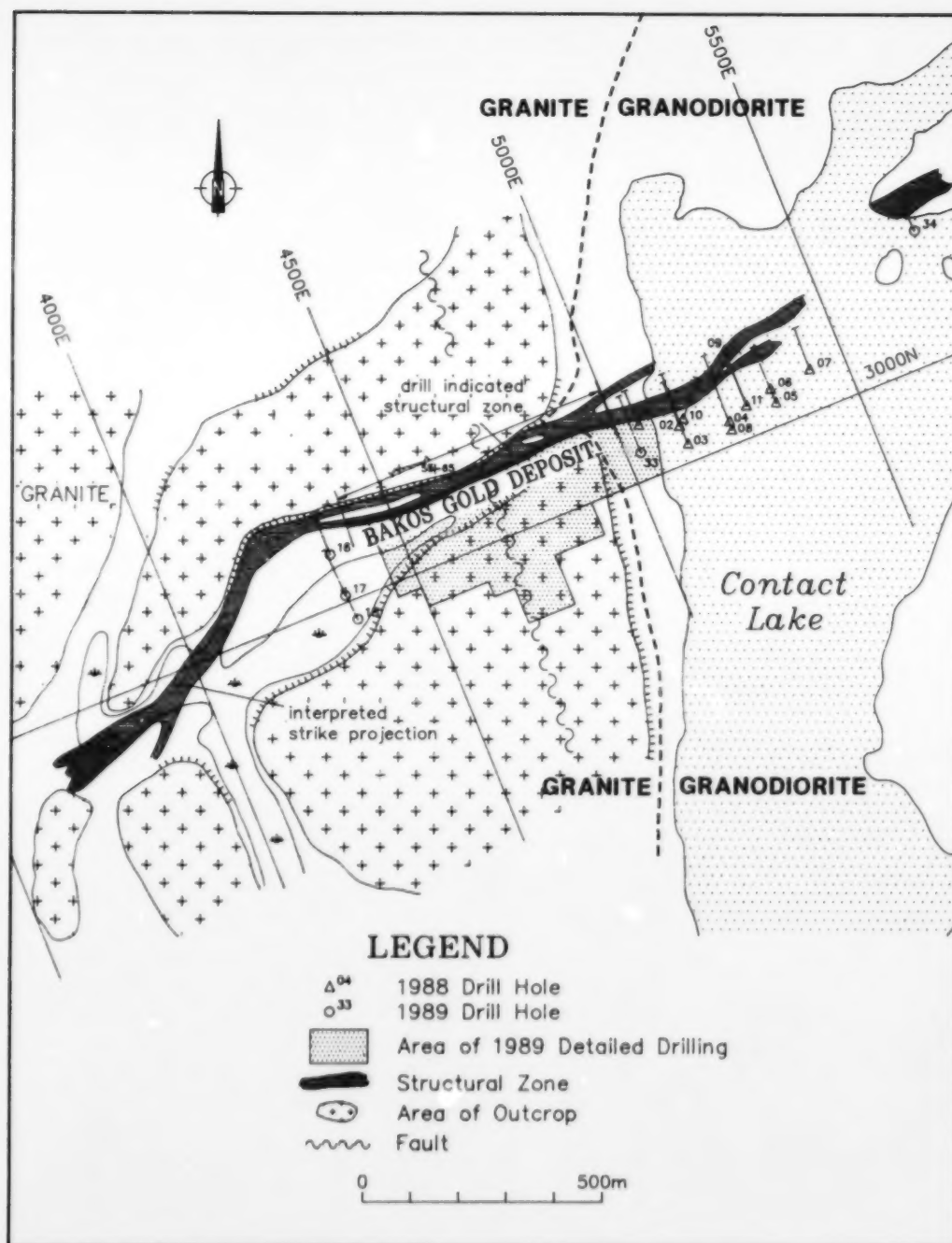


Figure 12 - Geological map of the Bakos deposit. Lines with small perpendicular ticks represent escarpments.

Whole rock geochemical analyses (Figure 13) and petrographic work indicate little or no alteration or trace element halo beyond the mapped 20-30 m width of the shear zone except possibly for sulphur ($>0.02\%S$), suggesting pyritization may extend for

several metres into the massive foot wall. Within the shear zone, the $K_2O - Na_2O$ ratios are affected only over 10 m in the area of the mineralization at the hanging wall.

Mineralization

The 1989 drill programs outlined a significant gold deposit over a 600 m strike length and to vertical depths of from 180 m to 280 m. The deposit currently remains open in all directions. The probable *in situ* reserve is estimated at 1.15 million tonnes grading 9.9 g/t (1,270,000 tons grading 0.29 oz/ton) Au for a total of 12,800 kg (370,000 ounces) of gold.

The gold mineralization occurs in several subparallel zones, however, one main zone is laterally continuous over much of the drilled area. This zone is typically developed adjacent to the structural hanging wall (Figure 14) but it tends to migrate into the central portion of the structure to the west and with depth. The main zone is auriferous over minimum widths of 1 to 3 m with a large proportion of the *in situ* reserve occurring in two thicker shoots. The east shoot (BK-1) is located within 200 m of the granite/granodiorite contact (Figure 15). It ranges from 3.7 to 15.0 m in true thickness and forms an irregularly-shaped, steeply southwest plunging lens. The west shoot (BK-2) from 3.1 to 6.8 m true thickness, forms a vertically dipping pipe-like body.

Gold values in the mineralized zones are associated with mm- to cm-scale clotted sulphide stringers and quartz veinlets (Plate 1D) that both parallel and cross-cut foliation. Gold concentration is proportional to clotty sulphide content, but there are no visible features indicating the limits of ore, which are defined by assay walls. The sulphides typically form 0.5 to 3% by volume and comprise pyrite > chalcopyrite > pyrrhotite, galena and trace amounts of sphalerite, molybdenite, chalcocite and boronite.

Visible gold is common and occurs as pinhead flakes adjacent to pyrite grains or within quartz veins. Silver is intimately associated with the gold and the average Au:Ag ratio for the deposit is 1:1.

Quartz veins may form 1 to 5% by volume of the mineralized zones and are rarely greater than 20 cm thick, but are up to 2 m in places. Very locally, quartz forms up to 40% of the rock over several metres. The quartz veins are typically cherty and highly strained where parallel to foliation, but they can be both white and non-strained (recrystallized?) within the stockwork zones.

Gold mineralization is associated with weak enrichments of other trace elements. Five mineralized samples (Table 2) display elevated values of Cu, Pb, As, Bi and Hg.

GEOLOGICAL HISTORY

The Bakos deposit is similar to other pluton- and shear-zone hosted lode gold deposits recently discovered in the La Ronge Belt. Much work remains to be completed on these deposits in terms of their genesis particularly with regard to their structural - metamorphic history. A general sequence of geological events is currently recognized as follows:

1. the intrusion of the Little Deer Lake Pluton into relatively unstrained country rocks;
2. brittle fracture development along a regional zone of weakness; potassic and fine-grained pyrite alteration, emplacement of quartz-pyrite-gold veins;
3. main shear zone development and formation of a penetrative foliation resulting in the main fabric of the structural zone;
4. lower amphibolite metamorphism; recrystallization of sulphides, silicates and gold, and
5. late brittle fracturing; retrograde greenschist facies minerals including hematite, marcasite and bornite, and possible redistribution of the gold and silica.

DISCUSSION

The discovery of the Bakos deposit is the result of per-

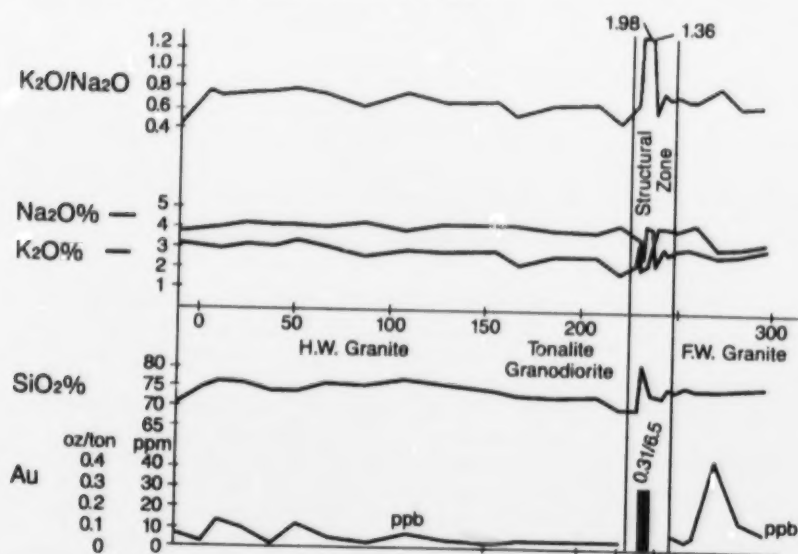


Figure 13 - Lithochemochemical profile, DDH 39. Horizontal scale is in metres.

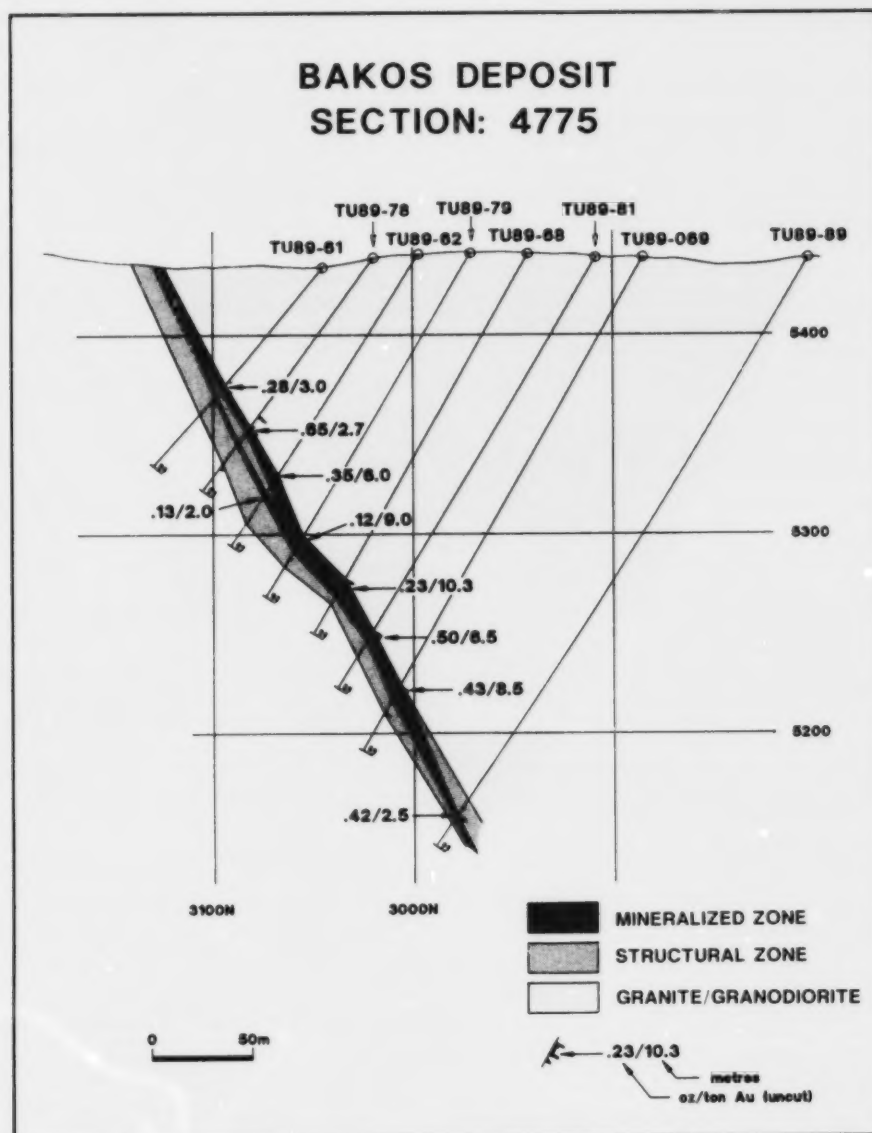


Figure 14 - Cross section (4775), Bakos deposit. Horizontal and vertical distances are in metres.

severance, a team effort and innovative exploration techniques. The search, which lasted five years, involved the integrated efforts of many people in the field and at the laboratories, and it drew on the support from management and joint venture partners.

The successful exploration programs consisted of a regional lake sediment sampling program followed-up by systematic bulk till sampling, glacial drift mapping, pebble studies and fine-fraction soil sampling. Once the gold-in-till train was delineated, geological

mapping and prospecting located a regional auriferous shear zone. IP-Resistivity surveys and a sonic overburden drill program localized drill targets. The initial drill program on land, comprised single holes separated by 200 m. Gold mineralization was intersected in all four holes and systematically followed up. None of the above exploration techniques, if used alone, would have located the deposit, however, in an integrated program they proved highly successful. Of the other exploration techniques employed, biogeochemical sampling may have been

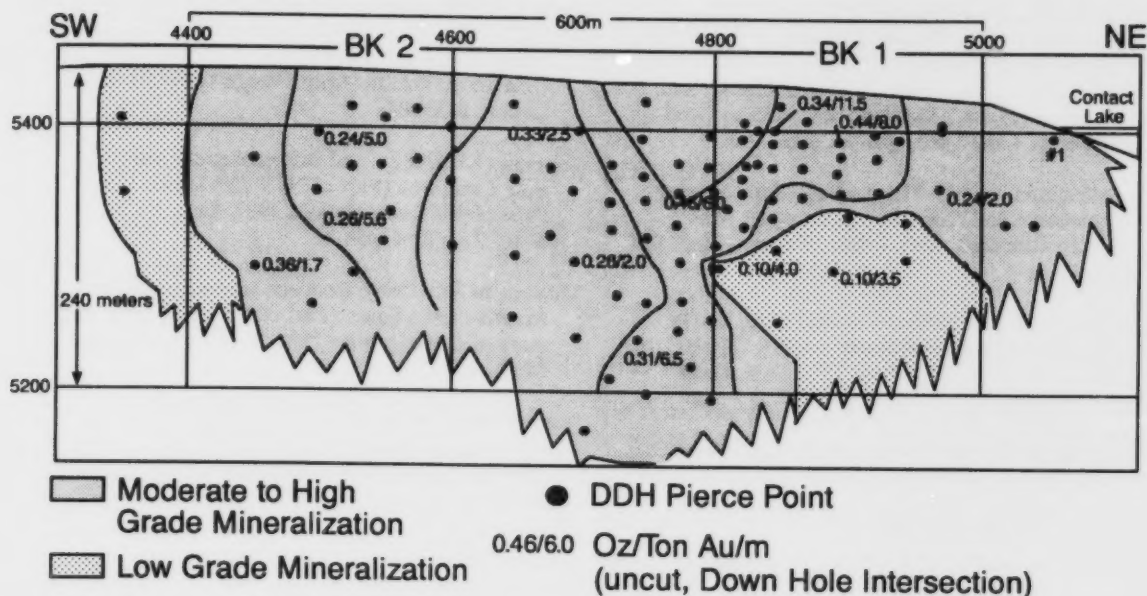


Figure 15 - Longitudinal section, Bakos deposit with diamond drill hole pierce points and selected assay results.

effective as a regional survey, but this type of sampling was terminated too early for results to be conclusive.

As this deposit has just recently been discovered, relatively little work has been done to understand the regional geological setting, the local structural controls, and the nature of the mineralizing fluids. Work in all of these disciplines is required to characterize the deposit and refine future exploration targets.

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Table 2 - Trace element geochemistry of four mineralized samples from the Bakos deposit.

S/N	Au	Ag	Cu	Zn	Pb	Te	Sb	As	W	Bi	Mo	Cr	V	Ni	Co	Ba	Hg
	oz/ton	oz/ton	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppb
44006	0.51	0.19	161	40	54	0.03	0.2	11	3	1.3	<5	124	7	2	4	1463	20
44011	1.48	3.83	4280	23	123	0.31	0.2	36	10	14.0	<5	132	4	3	8	827	260
44028	0.30	1.27	1201	15	109	0.30	0.2	20	3	67.0	<5	119	6	2	4	1067	320
44034	0.03	0.07	178	34	104	0.12	0.2	32	98	3.0	<5	143	19	6	2	1601	190

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ACKNOWLEDGEMENTS

The authors wish to thank Cameco and the joint venture partners for their continued support. Stuart Averill of Overburden Drilling Management Labs, and Janet Campbell and Allan Holsten of Saskatchewan Research Council, who have provided informative and helpful comments over the years. Dr. Jaap Hubregtse provided valuable petrographic observations on the mineralization and alteration. Field staff participating in the exploration programs are too numerous to name, but their efforts are greatly appreciated. Brian Bakos, in particular, contributed significantly during the prospecting phase. Tom Sibbald of Saskatchewan Energy and Mines, and Kieren Downes and Rick Kusmirski of Cameco critically reviewed the manuscript and provided many valuable suggestions. The Cameco drafting department and secretarial staff have been understanding and deserve a big thank you.

THE STRUCTURAL CONTROL OF SOME OF THE VEIN SYSTEMS AT THE DOME MINE, TIMMINS, ONTARIO

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EXTENDED ABSTRACT

GEOLOGICAL SETTING

The geological setting of the Dome mine is illustrated in Figure 1. The mine is on the north-dipping, south limb of the Porcupine Syncline. The rock units exposed in the mine workings include: iron-rich tholeiitic flows, and the felsic pyroclastic unit (Krist Formation) of the middle and upper formations respectively of the Tisdale Group; the turbiditic sediments of the Porcupine Group; and tabular bodies of quartz-feldspar porphyry. The 'younger sediments' of the Porcupine Group unconformably overlie the 'older sediments' of this group, and the volcanic rocks of the Tisdale Group. Within the mine, the general area of the unconformable contact of the sediments with the mafic flow rocks is referred to as the Greenstone Nose.

The South Greenstones is a unit of flows and sedimentary rocks which underlies the area south and east of the mine workings. The unit is bounded on the northwest and the west by the Dome Fault, and on the southeast by the Destor-Porcupine Fault. The South Greenstones are predominantly magnesium-rich tholeiitic flows, with carbonatized mafic and ultramafic komatiitic rocks at the base of the unit, in contact with the Dome Fault.

The Dome Fault strikes northeast and dips steeply to the southeast. In the vicinity of the Preston Porphyry (Figure 1), it swings north-south and dips at approximately 40° to the east. Quartz-feldspar porphyry intrusions emplaced along the Dome Fault have undergone at least the later stages of the regional deformation, which supports the contention of Hodgson (1983) that the fault is an early structure, probably related to the Destor-Porcupine Fault.

The volcanic rocks and associated sediments are folded about axes that plunge to the east and northeast. Within the mine, the unconformity surface (including the Greenstone Nose), the porphyry intrusions, and the long axes of deformed clasts, pillows and variolites, plunge between 30° and 40° east-

northeast. The mineral assemblages are characteristic of lower greenschist facies regional metamorphism.

VEIN SYSTEMS

The mine contains a large number of lode vein systems with a variety of morphologies and orientations, which are identified by the informal names assigned to them at the mine (Figure 1). The orebodies consist of gold-bearing quartz veins with varying amounts of carbonate (generally ferroan dolomite), tourmaline, and iron sulphides.

Ankerite Ore Units and Dacite Ore Units

The Ankerite ore units are characterized by continuous laminar structures (Figure 1), generally less than a metre thick, composed of quartz, ferroan dolomite and tourmaline veins. These units are identified by a dominance of veins or laminations of ferroan dolomite. The ore units occur in ductile shear zones, which are most prolific in variolitic mafic flows, and the veins parallel the shear planes or C-fabric of the shear zones. The shear fabric may be confined to the immediate vicinity of the ankerite unit, or it may extend for tens of metres to enclose several ankerite units in a highly foliated rock. The interlayering of the veins with sheared mafic rock, and the fine grain size of the vein quartz, give the units a sedimentary appearance. This is particularly apparent where the units are at flow contacts, but they also occur within flows.

The vein systems and the host shears strike between 050° and 080°, and dip approximately 70° to the north. Kinematic indicators are rare, but C-S fabrics and the vergence of folded shear fabrics and veins consistently indicate sinistral movement (Roberts, 1987). Boudinage structures (with associated ladder vein development), fold axes, and the long axes of variolites, plunge to the northeast in the plane of the shear.

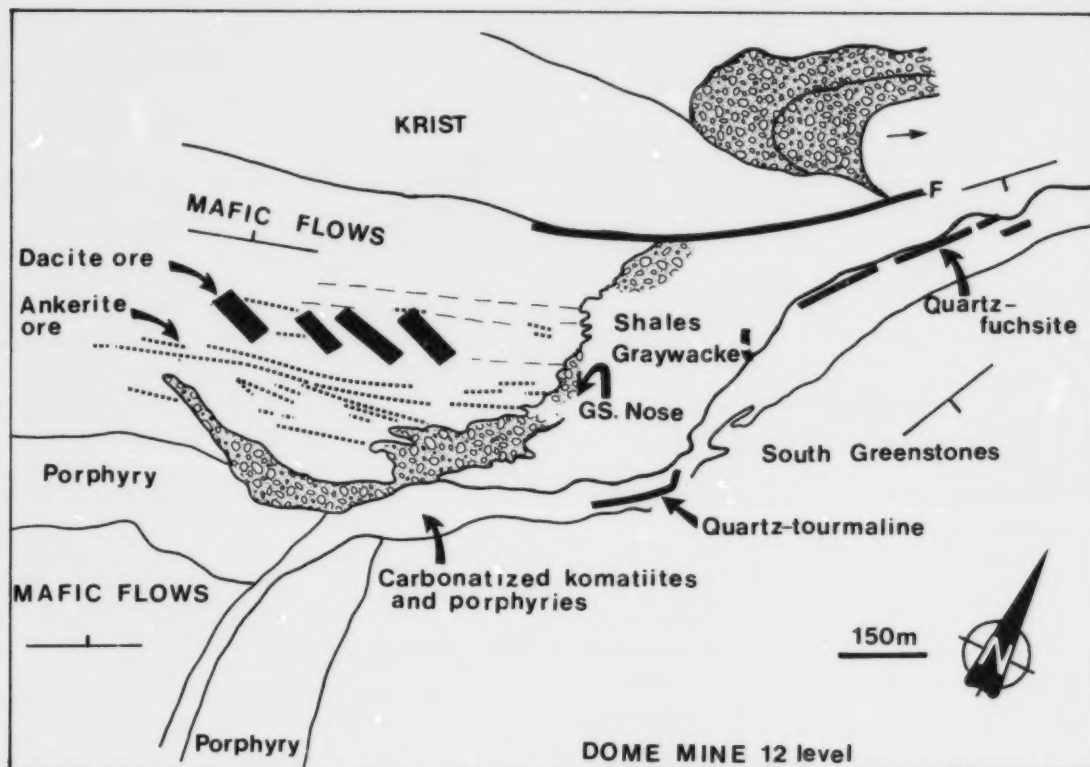


Figure 1 - Geological map of the 12th level of the Dome Mine (GS Nose indicates the Greenstone Nose). The Dome Fault lies in the zone of carbonatized komatiites and porphyry intrusions at the base of the South Greenstones.

The Dacite ore units are systems of quartz-tourmaline veins occurring in massive basalt flows overlying the variolitic flows. Most of the ore bodies are mined out, and the maps shown in Figure 2 are taken from mine records. The geometry of the ore units is characteristic of shear-hosted veins with a pattern indicating a system of P-shears and tension fractures in a dextral shear zone (Roberts, 1987). The ore units strike between 105° and 110° and dip to the north.

The pattern of the sinistral and dextral shears that host the Ankerite and Dacite ore units respectively, is one of intersecting shears with the geometry of a conjugate system developed by ductile or brittle-ductile rotational shear strain. Evidence for this type of deformation may be found in the fabrics of the host volcanic rock. The foliations in these rocks all dip to the north and may be classified into the following three groups, based on their strike attitudes: 90° , 70° , and 120° . The relationships between shearing and foliations is illustrated in Figures 3a and 3b. The 70° and 120° foliations are the result of deformation by rotational shear strain, and they define a system of intersecting shears which are penetrative at the scale of a hand specimen. Localized concentration of strain results in large shears (of both attitudes) which can

be readily observed at the scale of an outcrop (Figure 3a). With further concentration of strain and concomitant increase in the size of the shear, an outcrop may display the foliation of only one of the shear directions.

The 70° and 120° shears (and the foliations) intersect on a line plunging north and east, and it is assumed, in the absence of other evidence, that the direction of movement in each shear is perpendicular to this line. Thus the sense of movement on the 70° and 120° shears is compatible with bulk flattening about an east-west plane.

The east-west foliation is also penetrative, and locally, strain is concentrated along it to form sinistral shears (Figure 3a). This foliation is interpreted as an earlier foliation developed in the east-west plane of flattening. At a later stage, local movement on the foliation produced the sinistral shears.

A stretching lineation defined by deformed pillows and variolites plunges to the north and east, subparallel to the line formed by the intersection of the shears. Thus the direction of movement on the shears is approximately perpendicular to the direc-

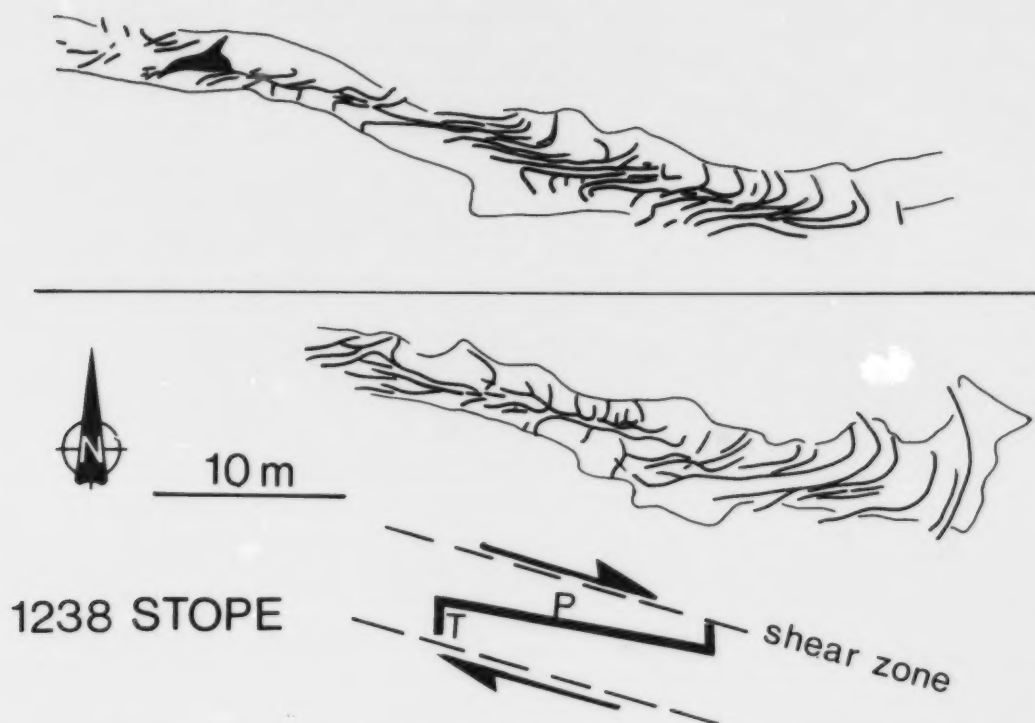


Figure 2 - Plan view of Dacite ore units. The geometry of the veins indicates a relationship to shearing indicated in the lower diagram.

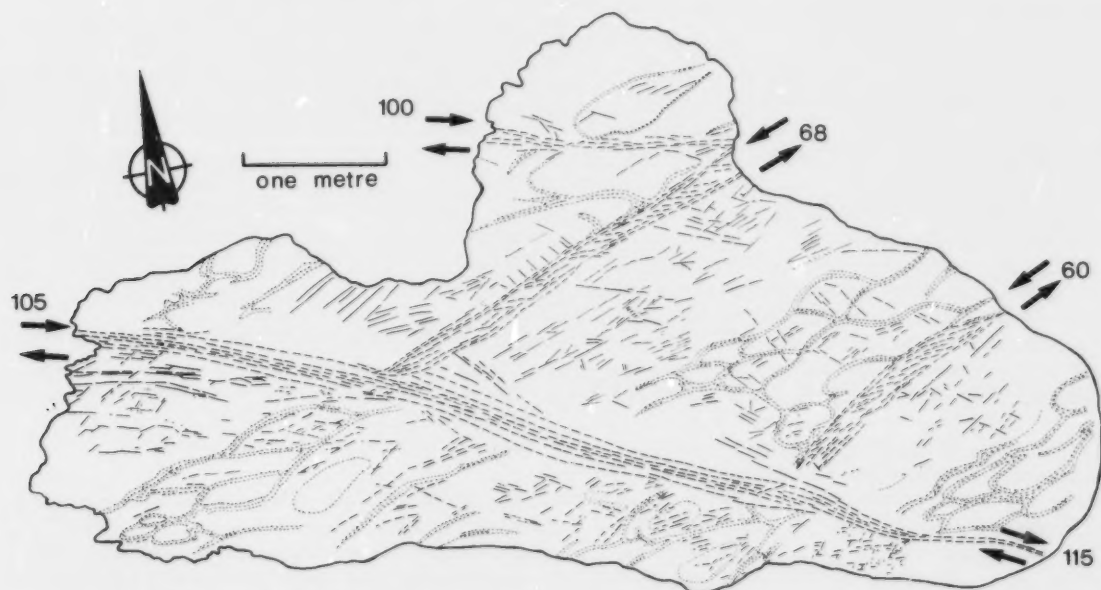


Figure 3a - A detailed map of a surface outcrop of pillowed volcanic rocks in the sequence that hosts the Ankerite and Dacite ore units at the Dome mine.

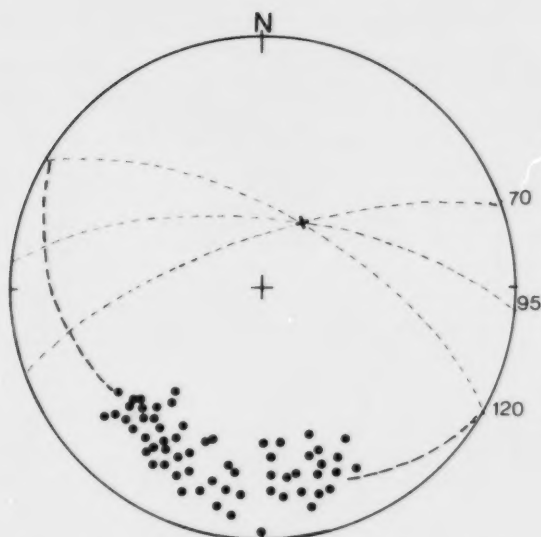


Figure 3b - A plot of foliations taken from the outcrop. The figure illustrates the genesis of the foliations in the area by rotational shear strain on a conjugate shear system in which the dominant shear directions are 070° (sinistral and host to the Ankerite ore units), and 120° (dextral, and host to the Dacite ore units). The east-west (sinistral) shears are interpreted as a plane of flattening on which later sinistral displacement took place. The shears occur at all scales, but strain is clearly inhomogeneous at the scale of the outcrop.

tion of stretching. This is not consistent with simple shear strain, but may be consistent with deformation by shearing combined with stresses acting across the shear which cause extensions approximately perpendicular to the direction of shear.

Vein Systems at the Greenstone Nose

The Ankerite and the Dacite ore units are hosted in shears, and consequently the orebodies are narrow tabular structures. In contrast, the vein systems at the Greenstone Nose (and elsewhere in the mine) are not confined to shears, but extend into the less strained rocks between the shears, where larger, more economically viable stopes, may be developed. The structure of the ore unit, and the geometrical relationship of the veins to the Ankerite units are illustrated in Figures 4a, b. Similar ore bodies occur elsewhere in the mine, as is illustrated in Figure 5.

The relationship of the quartz veins in the vein systems shown in Figures 4 and 5 is demonstrated in the detailed map of an Ankerite unit in Figure 6. The figure illustrates the development of conjugate fractures in the Ankerite unit that have the mechanical effect of stretching or extending the unit. The conjugate system of extension fractures are quartz-filled, although veining is better developed in the sinistral fractures than in the dextral fractures. In Figure 6, the

Ankerite unit is enclosed in a ductile, sheared, variolitic flow, and the extension fractures do not extend beyond the brittle material of the Ankerite ore unit. In Figures 4 and 5, however, the extension veins pass into the brittle rock between the shears hosting the Ankerite units.

One may conclude therefore, that the shear-hosted Ankerite and Dacite units are the response to bulk flattening about an east-west plane (shortening about a north-south axis). At a later stage of deformation, the planar structures associated with the Ankerite units acted as a mechanical inhomogeneity which resulted in the local reorientation of stresses to produce extension or flattening in the plane of the Ankerite units. In the more brittle rocks this is represented by quartz-filled fractures.

Quartz-Tourmaline and Quartz-Fuchsite Veins

The Quartz-fuchsite vein and the Quartz-tourmaline vein are emplaced in the Dome Fault at the base of the South Greenstone unit. The veins are in carbonatized, komatiitic mafic and ultramafic units, or, as in the case of the Quartz-fuchsite vein, at the contact of these units with sedimentary rocks of the Porcupine Group. The veins are comparatively simple, continuous, tabular structures, up to several metres thick, composed of massive and laminated quartz with accessory carbonate, fuchsite or tourmaline. C-S fabrics in the Dome Fault zone exposed at surface indicate sinistral movement, with the line of intersection of the C-S structures plunging 25° to the north-east, in the plane of the fault zone. This fabric is interpreted as a younger fabric associated with vein emplacement, which has been superimposed on the older fault structure.

CONCLUSIONS

1. The Ankerite and Dacite ore units occur in structures formed by rotational shear strain, which can be related directly to shortening along a north-south axis.
2. The Quartz-fuchsite and Quartz-tourmaline lodes were emplaced as a consequence of the reactivation of the Dome Fault (an older fault, probably related to the Destor-Porcupine Fault) during the same deformation as referred to in 1).
3. The various attitudes of the foliations in the vicinity of the Dome mine can be accounted for by a single deformation involving rotational shear strain, rather than a series of imposed deformations.

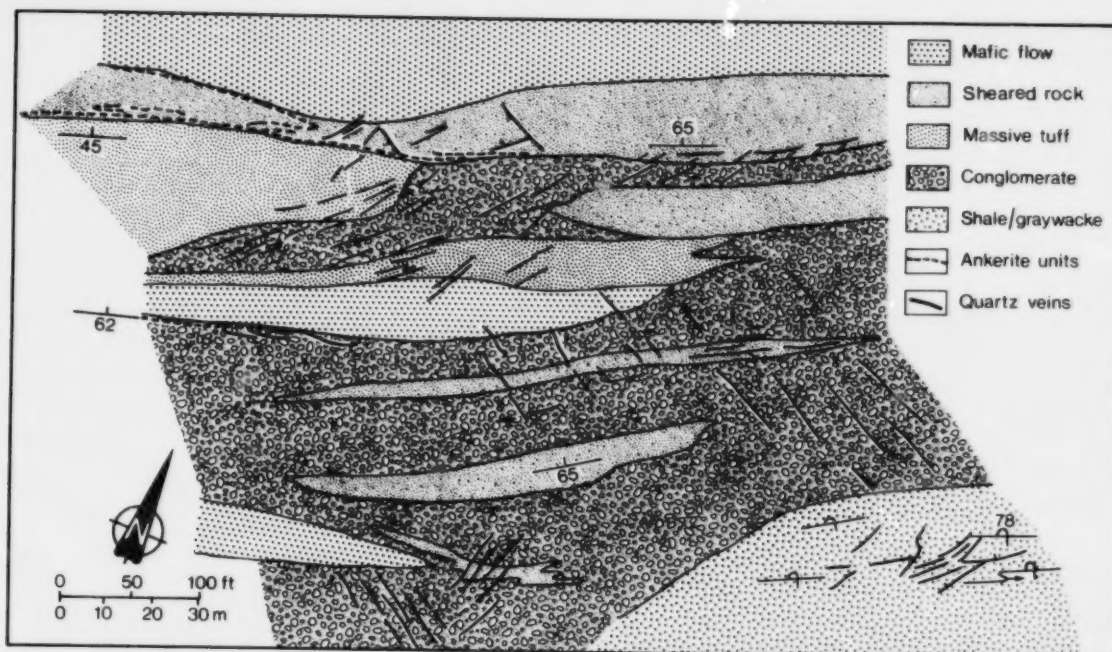


Figure 4a - A geological map of the Greenstone Nose area showing the relationship between Ankerite units, that are associated with highly sheared rocks, and quartz veins, that extend beyond the highly sheared rocks.

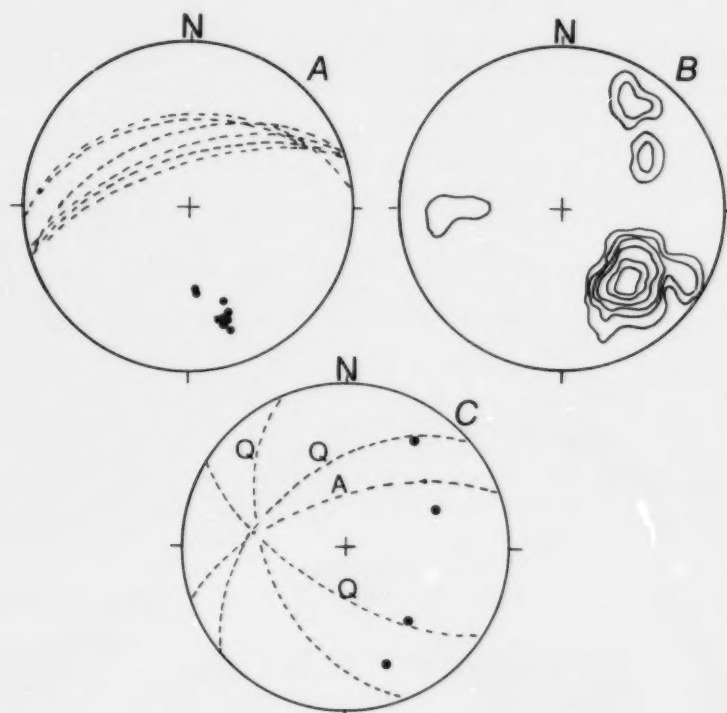


Figure 4b - The stereoplots show the geometrical relationships between the Ankerite units and the quartz veins. A. Orientation of the Ankerite units; B. Orientation of the quartz veins; C. A synoptic plot combining A and B.

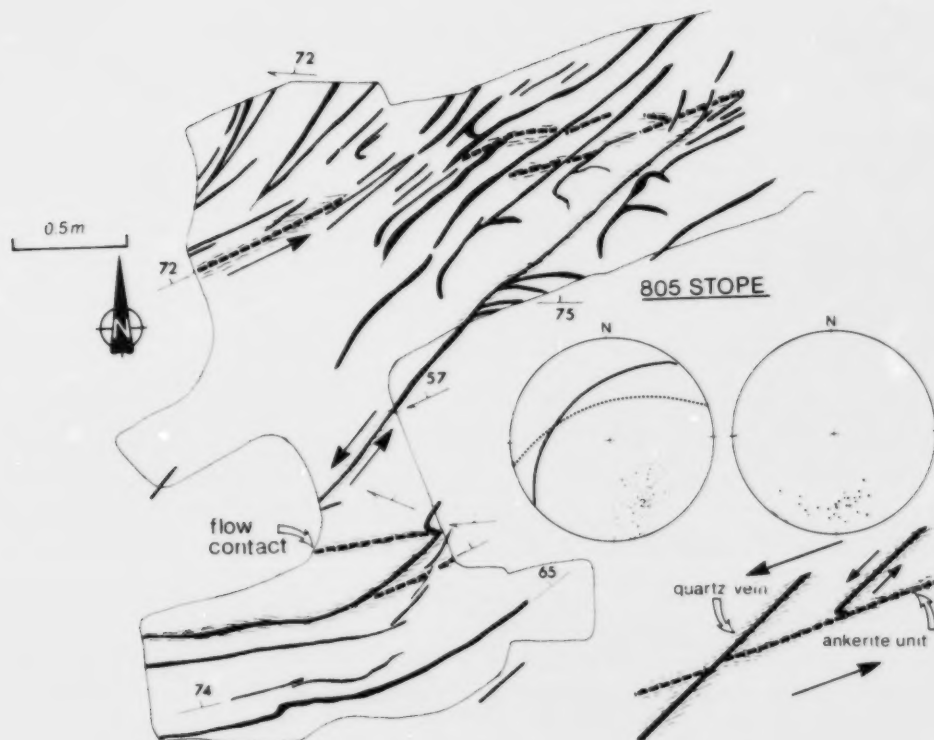


Figure 5 - The geological map illustrates the relationship between Ankerite units and quartz veins in volcanic flows, in which the quartz veins extend beyond the high strain zones associated with the Ankerite units. The stereoplots show the orientation of Ankerite units and quartz veins (right) and foliations (left).

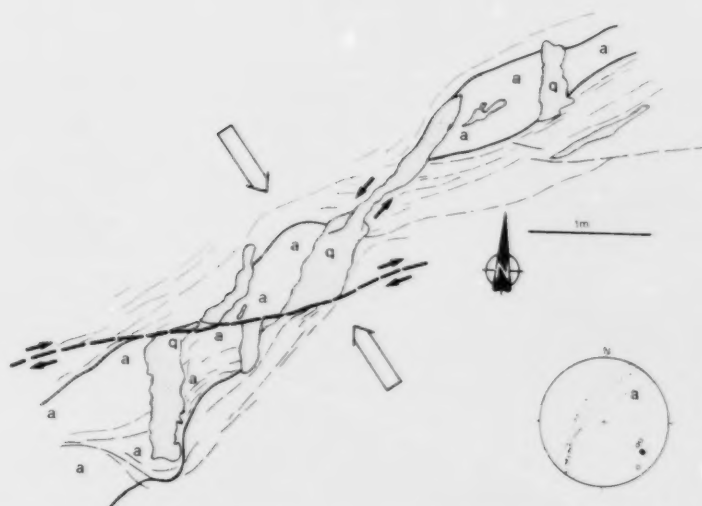


Figure 6 - A detailed map of part of an Ankerite unit (a) showing the development of later quartz veins (q) in conjugate shear fractures produced by flattening in a plane parallel to the Ankerite unit.

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EPIGENETIC GOLD MINERALIZATION IN THE FLIN FLON DOMAIN: FLUID CHARACTERISTICS

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ABSTRACT

The Flin Flon Domain consists of an Aphebian island arc sequence (Amisk Group) overlain by a synorogenic molasse deposit (Missi Group). These units have been intruded by a variety of ultramafic to granitic rocks, and have undergone polyphase deformation and metamorphism during the Hudsonian Orogeny. Economic mineralization consists of volcanogenic massive sulphides and numerous occurrences of epigenetic gold mineralization. All this mineralization represents the end product of focussed fluid flow events, which are intimately related to the geological development of the area. However, genetic models for the epigenetic gold mineralization, which are necessary to properly develop exploration strategies, have not been well constrained so far. Fluid inclusion and stable isotope data suggest that there are two significantly different fluids involved in pre-tectonic and syn- to post-tectonic gold mineralization, respectively, and allow development of preliminary genetic models that will aid in exploration.

The Laurel Lake deposit pre-dates the regional D2 event, and is hosted in Amisk Group quartz porphyry and lapilli tuffs. The ore consists of branching and crenulated quartz-muscovite-pyrite-tennantite-sphalerite-chalcopyrite-electrum veins, surrounded by a zone of sericitization and pyritization. Primary fluid inclusions contain H₂O-low density CO₂-NaCl (10.3 to >25 wt.% NaCl equiv.) fluids, with halite and nahcolite daughter solids. Quartz-muscovite pairs give oxygen isotope equilibration temperatures of 300 - 350°C, and oxygen and hydrogen isotopes suggest a possible seawater source for the mineralizing fluids. The seawater leached base and precious metals as it interacted with Amisk Group volcanic rocks.

Graham, Rio and Tartan Lake are examples of the later gold mineralizing event, and are related to shear zone development. The deposits are commonly quartz-pyrite-carbonate-tourmaline veins surrounded by a variably developed alteration halo of carbonate-quartz-feldspar-pyrite-K-mica-chlorite. Primary and secondary fluid inclusions characteristically contain H₂O-variable density CO₂ (0.60 to 1.03)-NaCl (<8.0 wt.% NaCl equiv.), and sometimes exhibit variable CO₂/H₂O ratios indicative of fluid unmixing. Oxygen isotope mineral pairs and fluid inclusions suggest that the deposits formed at temperatures of between 300 to 450°C, and at fluid pressures of 2 to 3 kbar. Oxygen and hydrogen isotopes suggest that metamorphic dehydration reactions are the source of the mineralizing fluids, which were then channelled into suitable structural traps. The likely gold precipitation mechanism was fluid unmixing resulting from a sudden pressure drop in dilatant zones.

INTRODUCTION

Mineralization in the western part of the Flin Flon Domain consists of syngenetic volcanogenic massive sulphides, and numerous occurrences of epigenetic gold mineralization (Bailes *et al.*, 1987; Coombe, 1984). In recent years the lithological and structural settings of many of the gold occurrences have been outlined (e.g. Pearson, 1980, 1981, 1983; Galley and

Franklin, 1987). The occurrences are hosted in a variety of lithologies, and are typically spatially associated with shear zones. This information on the geological setting of the occurrences has been used to construct preliminary genetic models (e.g. Pearson, 1987). It has been suggested that gold occurrences in the Amisk Lake area were formed from a hydrothermal system active during the latest stages of

volcanism and may represent epithermal-type deposits, while those in the Douglas Lake - Phantom Lake area are structurally-hosted, and considered to be either related to an evolving porphyry system or to the post-tectonic focussing of magmatic or metamorphic fluids along major shear zones. The objective of this paper is to refine these genetic models using fluid inclusion and stable isotope data from gold-bearing and barren veins to infer the characteristics of the fluids involved in the formation and development of the epigenetic gold mineralization in the area. Better constrained genetic models will aid in developing exploration strategies.

REGIONAL GEOLOGY

The Flin Flon Domain of northern Saskatchewan and Manitoba forms part of the Reindeer Zone of the Trans-Hudson Orogen (Figure 1) (Lewry, 1987). The oldest rocks in the western part of the Flin Flon Domain (Figure 2) are a sequence of tholeiitic to calc-alkaline volcanic rocks, termed the Amisk Group, that were deposited in an island arc tectonic

setting (Stauffer *et al.*, 1975; Gaskarth and Parslow, 1987). A Sm-Nd isochron age of 1875 ± 38 Ma was obtained from a suite of volcanic rocks in the Flin Flon area (Chauvel *et al.*, 1987), and U-Pb zircon studies have yielded ages of 1881 ± 2 Ma (McQuarrie, 1980) and 1886 ± 2 Ma (Gordon *et al.*, in press) for Amisk Group volcanism. Unconformably overlying the Amisk Group is a sequence of synorogenic alluvial fan and braided stream deposits, recently redefined as the Missi Formation by Stauffer (in press). A wide variety of intrusive bodies ranging in composition from gabbroic to granitic, and ranging in age from syn-volcanic to post-tectonic crosscut these supracrustal rocks (Stauffer, 1984). Zircons from the least deformed of these bodies, the Phantom Lake granite, give an age of 1827 ± 3 Ma (McQuarrie, 1980).

Most of the rocks in the area have undergone polyphase deformation and metamorphism during the Hudsonian Orogeny (Stauffer and Mukherjee, 1971; Bailes *et al.*, 1987). D1 deformation resulted in

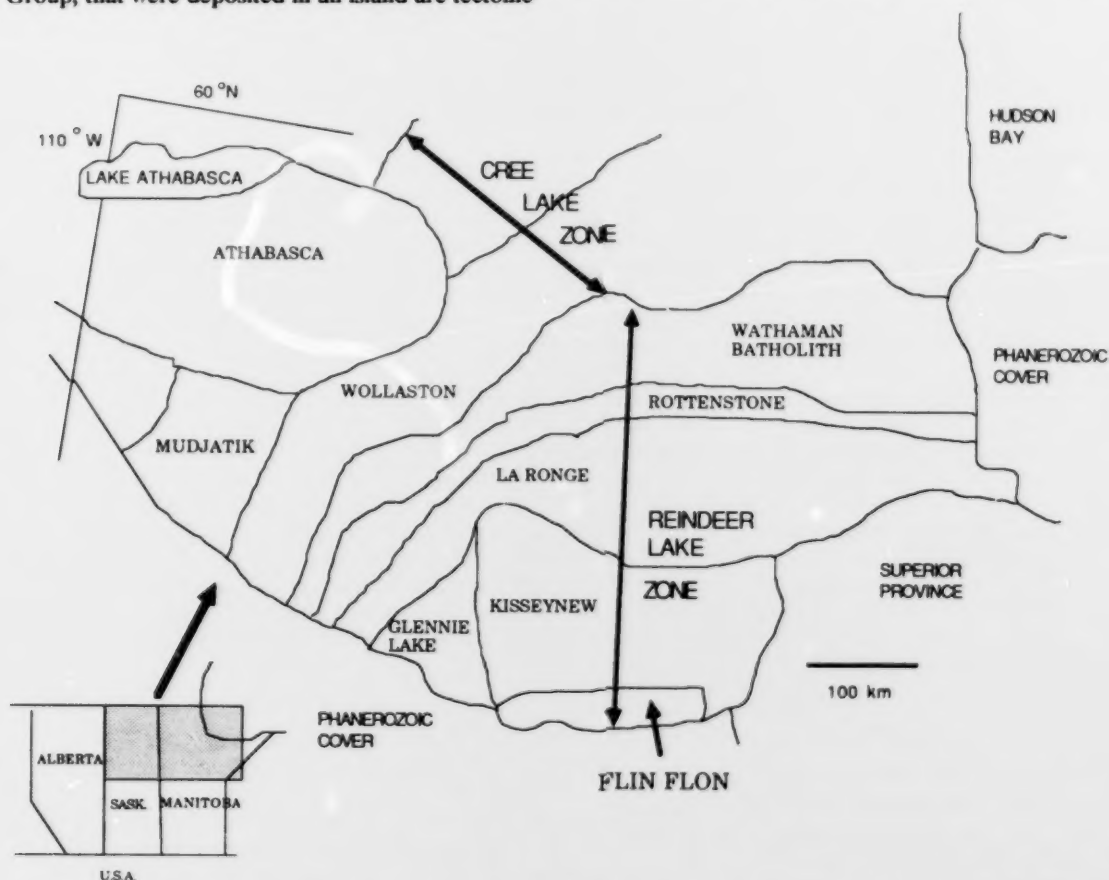


Figure 1 - Simplified map of the major lithotectonic domains of the Trans-Hudson Orogen, northern Saskatchewan and Manitoba (after Stauffer, 1984).

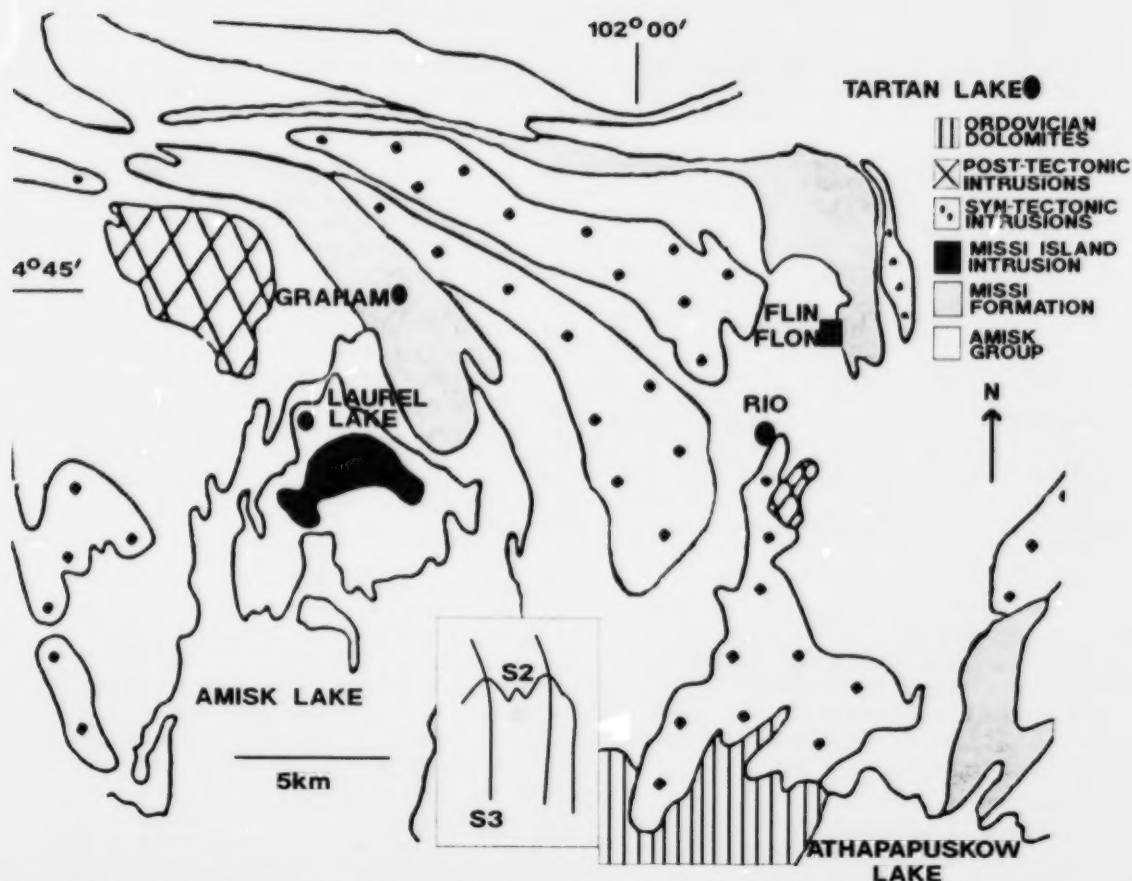


Figure 2 - Simplified geological map of the Flin Flon - Amisk Lake area, showing the location of Flin Flon, and the Laurel Lake, Rio, Tartan Lake, and Graham gold deposits (after Stauffer, 1984). The general orientations of schistosity in the area are shown in the inset.

the development of tight east-west-trending folds with no recognizable axial planar schistosity. D2 deformation resulted in major north- and northeast-trending folds with related strong axial planar cleavage (S2), while the D3 deformation event resulted in the formation of the northeast-trending Embury Lake antiform, crenulation of S2, and the development of the major fault zones in the area (Stauffer and Mukherjee, 1971). Recent mapping by Bailes and Syme (1987) shows that correlation of Amisk Group stratigraphy between fault blocks is not possible.

Peak regional metamorphism in the area was attained during D2, and metamorphic grade tends to increase eastwards and northwards from prehnite-pumpellyite facies in the vicinity of Flin Flon to amphibolite facies in the Snow Lake area, and near the contact with the Kisseynew Domain (Bailes and McRitchie, 1978; Aggarwal and Nesbitt, 1987). Retrograde metamorphism related to fluid move-

ment along the major D3 fault zones has been reported by Stauffer and Mukherjee (1971). The age of peak metamorphism and the cooling history of the area are poorly constrained because of the lack of isotopic studies on the intrusive bodies in the area and on well-characterized metamorphic minerals. A number of volcanic and intrusive rocks have been dated using Rb-Sr and K-Ar techniques (Mukherjee *et al.*, 1971; Watters and Armstrong, 1985; Lowdon *et al.*, 1963; Wanless *et al.*, 1965), yielding ages ranging from 1865 ± 5 to 1620 ± 80 Ma. These ages have been interpreted as either crystallization or metamorphic ages, but probably represent partially or completely reset ages resulting from fluid-rock interaction during or after metamorphism.

Regional structural correlations suggest that there are two distinct epigenetic gold mineralizing events (Pearson, 1987). The majority of gold occurrences are associated with shear zones and quartz veins that are syn-D2 to post-D3 in age. There is no association

with lithology, since occurrences are found in most rock types in the area. Examples of this type of mineralization, their host rocks and relevant references are listed in Table 1. The other episode of gold mineralization pre-dates the major deformation events, and is exemplified by the Laurel Lake deposit (Walker and McDougall, 1987). This deposit is hosted by felsic volcanic rocks and is not associated with a regional D3 shear zone.

Table 1 - Examples of Syn- to Post-tectonic Gold Mineralization.

Deposit	Host rocks	Reference
Rio	Basalt, granite dyke	Pearson (1984)
Tartan Lake	Basalt, gabbro	Fedorowich (1989)
Graham	Conglomerate	Pearson (1983)
Henning-Maloney	Diorite	Pearson (1983)
Newcor	Basalt	Pearson (1983)
Monarch	Greywacke	Pearson (1980)
Duplex	Basalt, greywacke	Pearson (1980)
Sonora	Greywacke	Pearson (1980)
Robinson Creek	Basalt, greywacke	Pearson (1982)
IMC-Cain B	Granite	Pearson (1983)

Both types of gold occurrences are the end result of focussed fluid flow events. The objective of this paper, by characterizing the fluids, is to ascertain whether distinct fluids were involved in the two epigenetic gold mineralizing events. The Laurel Lake, and Rio deposits were chosen as the type examples of the two mineralizing events.

USE OF FLUID INCLUSIONS AND STABLE ISOTOPES

Fluid inclusion studies and stable isotope compositions have provided important constraints on the genesis of a variety of ore deposits, including epithermal gold (Bodnar *et al.*, 1985; Field and Fifarek, 1985), mesothermal gold (Ho, 1987; Kerrich, 1987), volcanogenic massive sulphides (Pisutha-Arnond and Ohmoto, 1983) and copper porphyries (Taylor, 1974; Nash, 1976).

Fluid inclusions are classified into three types based on their origin: 1) primary inclusions, which are formed by sealing of crystallographic irregularities during initial crystal growth, 2) pseudosecondary inclusions, which form along fractures that develop during crystal growth and commonly define planar arrays that do not cross grain boundaries and 3) secondary inclusions, which are trapped by sealing of later fractures that crosscut grain boundaries. Thus, primary and pseudosecondary inclusions can provide information on the fluids present during mineral growth, whereas secondary inclusions record later fluid events.

Fluid inclusions can be used to determine the composition, density, and minimum temperatures of

various fluids, assuming that inclusion volume and composition has remained unchanged since entrapment. During analysis, the temperatures at which phase changes occur are recorded as the inclusions are alternately cooled and heated. The temperature of these phase changes, e.g. final melting temperature of solids, or homogenization temperatures, are compared to experimentally and empirically derived systems to determine the composition of the inclusion fluid. The homogenization temperature of an inclusion fluid defines the density if the liquid-vapour curve for the fluid is known. The inclusion may have been trapped at this temperature, or at a higher temperature corresponding to a higher pressure along the line of constant density (isochore). An independent estimate of the temperature or pressure of the fluid enables the actual temperature and pressure of trapping to be determined. The reader is referred to Roedder (1979; 1984) and Hollister and Crawford (1981) for more detail on fluid inclusion analytical techniques.

Water is the dominant component of ore-forming fluids. An important control on the fractionation of oxygen and hydrogen isotopes between water and minerals is temperature. The temperature dependant equilibrium fractionation factors commonly used in this type of study are summarized by Kyser (1987). In the present study, the oxygen and hydrogen isotopic composition of minerals (e.g. quartz and muscovite at Laurel Lake) in petrographic equilibrium were measured, and the temperatures at which the minerals equilibrated determined from the relevant isotope fractionation factors. The isotopic composition of the water from which they formed can then be calculated using this temperature and the appropriate mineral-water isotope fractionation factor.

Stable isotope data are reported as the deuterium/hydrogen (D/H) or ($^{18}\text{O}/^{16}\text{O}$) ratios in the sample relative to these ratios in Standard Mean Ocean Water (SMOW), in units of permil, e.g.

$$\delta^{18}\text{O} = \left(\frac{(^{18}\text{O}/^{16}\text{O})_{\text{sample}}}{(^{18}\text{O}/^{16}\text{O})_{\text{SMOW}}} \right) - 1 \times 100$$

Fortunately, natural waters of different origins exhibit significant differences in their ^{18}O and D contents, so that their isotopic composition can be used as a tracer for the source of the water, and as a means of determining the extent of interaction with the surrounding rocks. The reader is referred to Taylor (1979), Ohmoto (1986) and Taylor (1987) for further information on the use of stable isotopes in the study of ore deposits.

LAUREL LAKE DEPOSIT

Geological Setting

The geology and geochemistry of the Laurel Lake deposit has been described in detail by Walker and McDougall (1987) and Ansdell and Kyser (in press). The deposit consists of branching quartz-sulphide veins hosted by a sequence of Amisk Group porphyritic rhyolites and felsic fragmental rocks, which are, in turn, sandwiched between basaltic and dacitic lavas and tuffs (Figure 3). These volcanic rocks may be related to the Missi Island Intrusion, an altered trondhjemite, which is thought to represent the core of a volcanic vent complex (Chute and Ayres, 1977). The host rocks to the deposit have been deformed by two deformation events, manifested by the preferred orientation of muscovite flakes. These two events can be correlated with the regional D2 and D3 events (Stauffer and Mukherjee, 1971). The veins are crenulated by D3, but Walker and McDougall (1987) observed that sericite clots are flattened along S2 and folded by S3 suggesting that alteration preceded

regional D2 deformation. In places, disseminated pyrite grains parallel muscovites that define S2, and are folded during S3. Overall, mineralization appears to pre-date the D2 and D3 deformation events, as well as metamorphism.

Mineralization consists of anastomosing quartz-muscovite-pyrite-sphalerite-tennantite-galena-chalcocopyrite veins, with minor amounts of electrum, arsenopyrite, stibnite and altaite, surrounded by a wide, pervasively sericitized and pyritized hydrothermal alteration zone (Walker and McDougall, 1987; Ansdell and Kyser, in press). The average Au/Ag ratio in the mineralization is 1:5. The textural relationship between sulphides, and the paragenesis outlined in Figure 4 is predominantly a function of deformation during low-grade metamorphism. Pyrite and arsenopyrite deform in a brittle manner, whereas the other sulphides are more prone to ductile deformation under these conditions (e.g. Craig, 1983). The sulphide-rich veins are termed Stage 1 veins, and are crosscut by quartz-tourmaline-dolomite-pyrite veins (Stage 2). Stage 2 veins crosscut foliation, but show evidence of strain suggesting that they post-date the most intense D2 deformation but pre-date a later deformation event.

Fluid Characteristics

Fluid inclusions in quartz from Stage 1 and 2 veins were examined. Isolated, obvious primary inclusions are rare in both vein stages. Pseudosecondary and secondary planar arrays predominate, but their relative timing is difficult to determine. There is, however, a detectable difference in composition between the inclusions related to quartz growth (primary and pseudosecondary) in Stage 1 and 2 veins.

In Stage 1 veins primary and pseudosecondary H₂O-CO₂ inclusions contain daughter minerals of halite and nahcolite (?). The CO₂ volume is variable, but is generally less than 50 volume percent. Unfortunately, the inclusions decrepitate between 250° and 305°C before the halite daughter minerals dissolve, thus the salinity of these inclusions can only be constrained to >25 weight percent NaCl equivalent. There are also pseudosecondary H₂O-CO₂ inclusions in Stage 1 veins that do not contain daughter minerals. These have salinities ranging from 10.3 to 20.6 weight percent NaCl equivalent, and mole fractions of CO₂ (XCO₂) of less than 0.16.

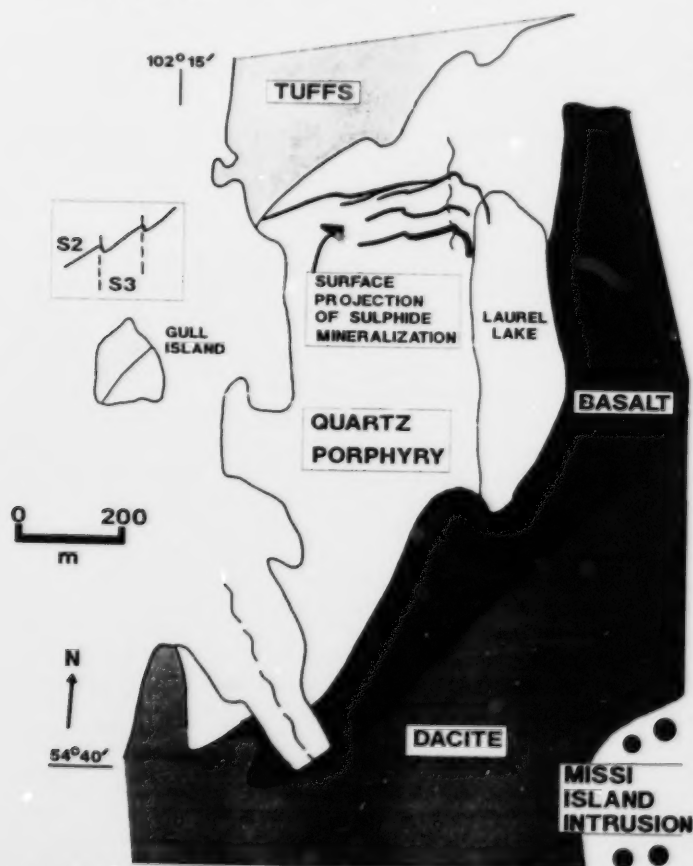


Figure 3 - Geological map of the Laurel Lake deposit. The orientations of the dominant schistosity in the area are shown in the inset.

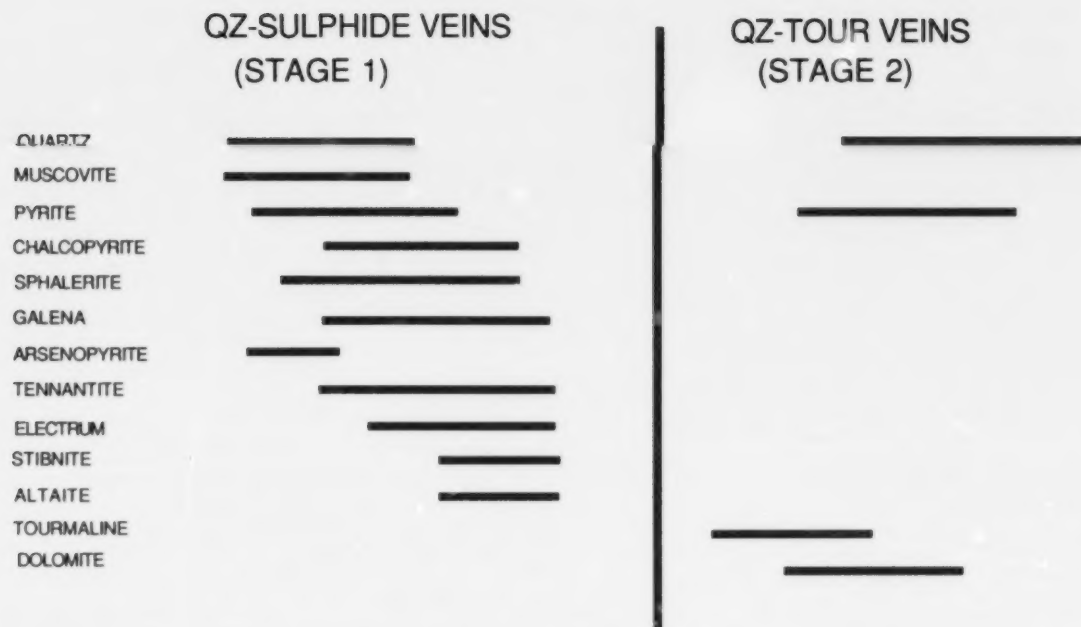


Figure 4 - Mineral paragenesis of the auriferous Stage 1 quartz-sulphide veins and the non-auriferous, Stage 2 quartz-tourmaline veins in the Laurel Lake deposit.

Primary, pseudosecondary and secondary inclusions in Stage 2 veins are predominantly H_2O-CO_2 bearing. The range in salinity and XCO_2 of inclusions in Stage 2 veins (2.0 to 7.4 wt.% NaCl equiv.; XCO_2 - 0.09 to 0.37) indicates that these veins formed from less saline, but more CO_2 -rich fluids than the Stage 1 mineralized veins. Within Stage 2 veins there is no distinct difference in salinity between primary, pseudosecondary and secondary H_2O-CO_2 inclusions. There are also rare primary and secondary $H_2O-NaCl-(CaCl_2)$ inclusions in Stage 2 veins, with salinities of up to 7.5 weight percent NaCl equivalent.

Secondary inclusions in Stage 1 veins are typically H_2O-CO_2 inclusions, but have lower salinities (6.8 to 7.0 wt.% NaCl equiv.) and more variable XCO_2 (0.05 to 0.41) than primary and pseudosecondary inclusions in the same veins. Some of these secondary fluid inclusions in Stage 1 veins may represent fluids that were circulating during the formation of the Stage 2 veins.

In summary, there is a distinct difference in the salinity of the fluids which deposited the Stage 1 and 2 veins. Stage 1 veins were deposited from H_2O-CO_2 fluids having salinities ranging from 10.3 to greater than 25 weight percent NaCl equivalent, whereas Stage 2 veins were deposited from H_2O-CO_2 fluids with salinities ranging from 2.0 to 7.5 weight percent NaCl equivalent.

All fluid inclusions tend to decrepitate (224 - 380°C) before homogenizing, but one secondary H_2O-CO_2 inclusion in a Stage 1 vein homogenizes to liquid at 276°C, whereas a $H_2O-NaCl$ primary inclusion in a Stage 2 vein homogenizes to liquid at 280°C. The homogenization and decrepitation temperatures provide minimum temperature estimates of the fluids involved in the formation of Stage 1 and Stage 2 veins.

Quartz, muscovite and tourmaline were separated from Stage 1 and Stage 2 veins, and from altered felsic volcanic rocks so that their oxygen and hydrogen isotopic compositions could be measured. These values are used to calculate the temperature at which the minerals formed, and to determine the composition of the fluid from which they formed.

There is no significant difference in the $\delta^{18}O$ values of quartz from either vein stage, or from altered felsic volcanic rocks. The $\delta^{18}O$ values for quartz from the altered felsic rocks range from 11.9 to 12.7 permil; from Stage 1 veins from 12.0 to 13.2 permil and from Stage 2 veins from 12.1 to 13.7 permil. Muscovites from altered felsic rocks have $\delta^{18}O$ values that range from 9.0 to 10.0 permil, a range that includes the $\delta^{18}O$ value of muscovite from a Stage 1 vein. The two Stage 2 tourmalines analyzed have $\delta^{18}O$ values of 9.7 and 9.9 permil. Using the fractionation factors of Clayton *et al.*, (1972), O'Neil and Taylor (1969), and King and Kerrich (in prep.) to calculate the oxygen isotope equilibration temperatures,

quartz-mineral pairs from Stage 1 and 2 veins, and altered felsic volcanic rocks give consistent oxygen isotope equilibration temperatures of 300 to 350°C.

Although the oxygen isotopic composition of the various muscovites are similar, there is a range in their hydrogen isotopic compositions. A Stage 1 vein muscovite has a δD value of -47 permil, whereas the δD values of muscovites in altered felsic rocks range from -50 to -79 permil. Muscovites in Stage 1 veins are coarse grained (up to 500 μm) compared to those in the altered felsic volcanic rocks (up to 200 μm), and may be less susceptible to exchange with later fluids.

The calculated oxygen and hydrogen isotopic compositions of the fluids involved in the formation and development of the Laurel Lake deposit are shown in Figure 5. Stage 1 hydrothermal fluids do not appear to be magmatic or normal metamorphic fluids. A likely source is seawater that has been modified by interaction with the volcanic and intrusive rocks in the area. As heated seawater interacts with volcanic

rocks, the δD and $\delta^{18}O$ values of both seawater and rocks change depending on the weight ratio of water to rock. At high water/rock ratios (e.g. > 10), the isotopic composition of the hydrothermal fluid is least affected by the rocks and is close to seawater, whereas at very small water/rock ratios (i.e. < 0.01) where most of the reservoir of hydrogen and oxygen is in the rocks rather than the water, the isotopic composition of the fluid is controlled by the isotopic composition of the rock. At intermediate water/rock ratios (e.g. 0.05 - 1.0), the reservoir of hydrogen is in the fluid whereas the reservoir of oxygen is in the rocks so that the $\delta^{18}O$ value of the fluid increases whereas the δD value is unaffected. The isotopic compositions of fluids associated with Stage 1 veins are similar to that of evolved seawater after interacting with rocks at a temperature of between 300 and 350°C and a water/rock ratio of about 0.1. The muscovites from the altered felsic rocks have lower δD values and probably record recrystallization and interaction with fluids during metamorphism.

The calculated oxygen and hydrogen isotopic compositions of the fluids in equilibrium at 350°C with Stage 2 quartz-tourmaline veins are very similar to those calculated for Stage 1 veins. Although the fluids may have had a similar source, the chemical composition of the two fluids are distinct as reflected by both the mineralogy and fluid inclusion composition of the veins.

The geology and fluid characteristics of the Laurel Lake mineralization can be used to constrain the genesis of the deposit. The high salinity of the Stage 1 hydrothermal fluids are atypical of both epithermal (Bodnar *et al.*, 1985) and mesothermal gold deposits (Ho, 1987; Robert and Kelly, 1987). In addition, the temperature of mineralization is low when compared to gold associated with porphyry systems. A simplified model for the genesis of the Laurel Lake deposit is shown in Figure 6. Seawater, the likely source of the hydrothermal fluids, circulated through Amisk Group volcanic rocks and leached base and precious metals. Pressure estimates using fluid inclusion and stable isotope data give ambiguous results for Stage 1 mineralization that vary between 1.5 and 4.0 kbar. This range probably results from partial re-equilibration

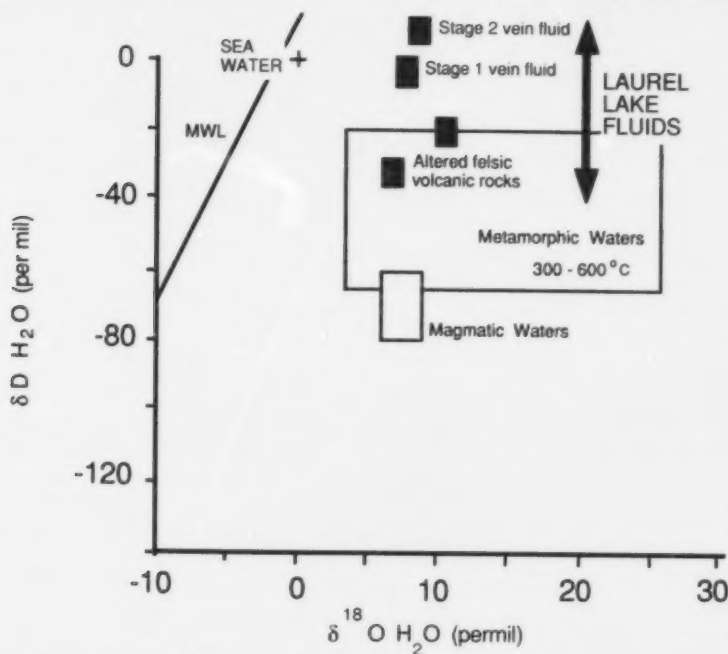


Figure 5 - δD and $\delta^{18}O$ values of the calculated composition of fluids in equilibrium with Stage 1 quartz and muscovite, Stage 2 quartz and tourmaline, and quartz and muscovite in the altered felsic volcanic rocks at the Laurel Lake deposit. The coarse Stage 1 vein muscovites may have been less susceptible to exchange with a later fluid, and may be representative of the isotopic composition of the mineralizing fluid. The fine-grained muscovites in the altered felsic volcanic rocks record recrystallization and interaction with fluids during metamorphism. The isotopic composition of the fluids were calculated using the equilibrium fractionation factors of Clayton *et al.* (1972), O'Neil and Taylor (1969), King and Kerrich (1990), and Suzuoki and Epstein (1976), and a temperature of 300°C. Values for seawater, meteoric waters (MWL), magmatic waters, and metamorphic waters are also shown for reference.

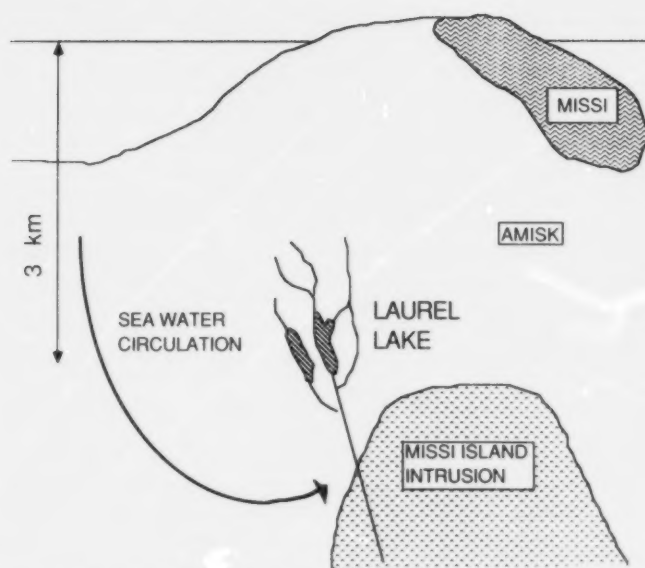


Figure 6 - Schematic model for Laurel Lake gold mineralization. The calculated isotopic composition of the Stage 1 fluids suggest that seawater was the major component. Au, Ag, and base metals were leached from Amisk Group volcanic rocks and concentrated in branching veins within a sequence of felsic volcanic rocks, probably as a result of a decrease in temperature, or unmixing of H_2O and CO_2 . The depth of mineralization is poorly constrained, although the mineralogy and fluid composition is not typical of either epithermal or mesothermal gold mineralization. The temporal relationship among mineralization, the Missi Island Intrusion, and Missi Group sedimentation is poorly constrained at present.

of fluid inclusions densities during metamorphism. However, the mineralization is only associated with Amisk Group volcanic rocks, pre-dates regional metamorphism, and consists of anastomosing veins that may have represented a localized zone of brittle fracturing. These geological characteristics, and the lack of evidence for the involvement of fluids from a deep metamorphic or magmatic source in the formation of the deposit suggests that a relatively shallow depth of formation (about 3 km) may be reasonable. There does not appear to be any evidence for fluid mixing at the site of deposition, and so other mechanisms, such as a decrease in temperature or unmixing of H_2O and CO_2 , may be responsible for deposition of the ore.

RIO DEPOSIT

Geological Setting

The Rio deposit is the largest gold occurrence associated with a conjugate set of shear zones in the Phantom Lake - Douglas Lake area (Figure 7) (Galley and Franklin, 1987). The geology of the deposit has been described previously by Pearson (1984) and Middleton (1985). The hanging wall side of the Rio Fault consists of westward-facing inter-

bedded basalts and debris flows of the Amisk Group, while the footwall side comprises basalts enclosed by the diorite phase of the Boot Lake intrusive complex (Figure 8). The youngest intrusive in the area, the Phantom Lake Granite, has a U-Pb age of 1820 Ma (McQuarrie 1980) and is represented in the vicinity of the Rio deposit by an irregular-shaped dyke. The Rio Fault and the hydrothermal alteration related to mineralization crosscut and overprint this dyke, emphasizing that the gold mineralization post-dates the main geological events in the area.

On surface, the deposit consists of a wide zone of silica - ankerite alteration, which is concentrated in the area where basalts are on either side of the fault and where there is a change in orientation of the Rio Fault (Figure 8). In detail, three different ore associations, including the WC (hanging wall), AJ (footwall) and PLG (dyke) types, occur within the alteration zone, but can only be distinguished underground (Figure 9).

The WC, or 'hanging wall' mineralization occurs as lensoid bodies that trend about 025° and consist of fine-grained, pervasive quartz-ankerite-albite-pyrite alteration.

AJ, or 'footwall', mineralization is more vein-controlled, and consists of anastomosing quartz-ankerite-pyrite-(chlorite-tourmaline-muscovite) veins, up to 0.5 m wide, surrounded by variably developed alteration zones up to 3 m wide. Alteration is not always symmetrical about the veins, and in many places quartz veins define the edge of the altered zone, suggesting that the veins post-date the alteration. A general zonation of alteration in the AJ mineralization is apparent, with a quartz-ankerite-albite-pyrite-chlorite brecciated zone near the centre, passing into an ankerite-quartz-chlorite-pyrite outer zone, which is cut by chlorite-ankerite-pyrite veinlets. Apparently unaltered basalts bordering the outer zone comprise chlorite-plagioclase-epidote-calcite-muscovite-pyrite, and are commonly cut by calcite-quartz veinlets.

The PLG, or 'dyke' mineralization consists of quartz-(ankerite-pyrite-muscovite)-filled tension gash veins hosted by highly deformed Phantom Lake granite dyke. The veins tend to occur along the dyke margin or in fold hinges in the dyke, suggesting that this mineralization developed at a time of ductility contrast between the granite and surrounding basalts. Adjacent to the tension gash veins the dyke comprises quartz-albite-muscovite-carbonate-pyrite-hematite. A change in major and trace element

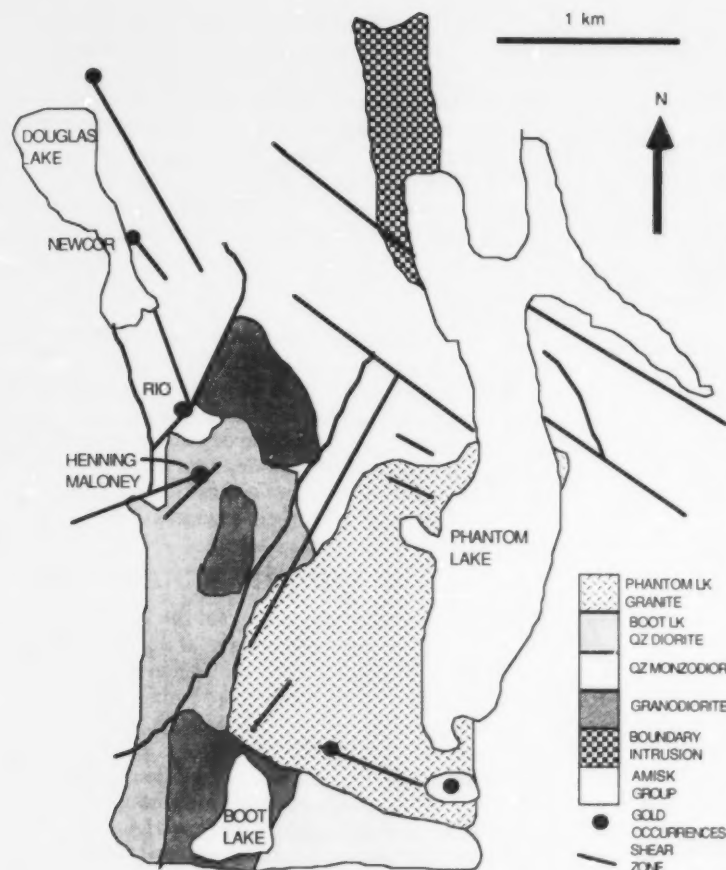


Figure 7 - Simplified geological map of the Phantom Lake - Douglas Lake area, showing the location of the Rio, Henning-Maloney, and Newcor deposits, and other gold occurrences in relation to shear zones. Modified after Galley and Franklin (1987).

chemistry of the Phantom Lake granite during progressive hydrothermal alteration (highlighted in Table 2) results from intensive albitization, carbonatization and pyritization. Böhlke (1989) describes similar alteration characteristics in the Sierra Nevada gold deposits, California.

Gold in all ore types, occurs as inclusions in pyrite, or along pyrite grain boundaries. Cross-cutting relationships between the three ore types are not seen, although in all types the quartz vein mineralization appears to post-date the finer-grained, quartz-carbonate - dominated alteration. Pearson (1984) indicates that fractures trending 170° , parallel to the general trend of AJ veins, crosscut fractures trending at 025° , the trend of WC alteration, suggesting that the pervasive WC alteration may pre-date AJ mineralization and alteration.

Fluid Characteristics

Fluid inclusions in quartz vein samples from the AJ and PLG zones include primary, pseudosecondary and secondary types. They are dominantly H_2O-CO_2 inclusions, with a highly variable volume percent CO_2 (15 to 100). Inclusions that appear to be pure CO_2 however, can contain up to 15 volume percent H_2O . The water forms a thin film along the inclusion walls and is difficult to see in rounded inclusions. Generally, the volume percent CO_2 tends to be more constant within a particular group of primary inclusions, or planes of pseudosecondary and secondary inclusions. The melting point of CO_2 , in all generations of fluid inclusions, ranges from -56.6 to $-57.1^\circ C$ in AJ veins, and from -57.0 to $57.4^\circ C$ for the PLG vein suggesting that the inclusions contain very little CH_4 (Hollister and Burruss, 1976). Unfortunately, in this study, the melting point of the CO_2 clathrate (CO_2 5.75 H_2O) can only be used to determine the salinity of the fluid (Collins, 1979) in a few cases, because the CO_2 phase commonly homogenizes before the clathrate melts. The salinity of inclusion fluids in both AJ and PLG veins is less than 4 weight percent NaCl equivalent. The homogenization of CO_2 to the liquid phase ranges from -18.6 to $21.8^\circ C$ indicating a CO_2 density range from 1.03 to 0.75 g/cc, although a much smaller range is obtained for individual arrays of inclusions. There is no distinct difference between the CO_2 homogenization temperatures obtained from the AJ and PLG veins. The broad range of CO_2 density is generally considered to represent pressure fluctuations at the time of entrapment. All inclusions decrepitate between 175 and $285^\circ C$ prior to bulk homogenization, although two inclusions did homogenize to the vapour phase at $220^\circ C$ and $329^\circ C$.

The last fluid event represented by the fluid inclusions are planes of aqueous secondary inclusions with greater than 80% liquid, salinities of between 7 and 14 weight percent NaCl equivalent, and temperatures of homogenization to the liquid phase from 110° to $225^\circ C$. Although the absolute timing of this event is difficult to determine it is probably related to uplift after gold mineralization.

Table 2 - Major and Trace Element Compositions of Unaltered and Altered Phantom Lake Granite.

Sample #	449	179	311	209
	Centre of Phantom Lake Granite	Dyke near Rio Fault	Weakly altered dyke Rio, 240'	Altered dyke with veins Rio, 215'
SiO ₂	67.9	64.9	58.3	50.4
TiO ₂	0.36	0.67	0.68	0.54
Al ₂ O ₃	15.6	16.1	17.7	14.5
Fe ₂ O ₃	2.57	3.91	2.85	5.95
MnO	0.04	0.04	0.07	0.12
MgO	1.19	1.47	1.31	2.66
CaO	1.58	2.68	3.98	7.37
Na ₂ O	4.74	5.20	9.59	8.06
K ₂ O	4.50	3.00	0.77	0.36
P ₂ O ₅	0.15	0.27	0.31	0.29
LOI	1.31	1.23	4.85	8.62
TOTAL	100.3	99.9	100.5	99.0
Cr	27	25	33	24
Rb	76	68	29	23
Sr	1480	1700	537	608
Y	< 10	< 10	< 10	< 10
Zr	128	121	172	119
Nb	13	< 10	11	< 10
Ba	1680	1620	241	104

Oxygen isotope mineral pairs can provide further constraints on the temperature of mineralization. A quartz (10.3 permil)-chlorite (3.8 permil), and a quartz (10.1 permil)-tourmaline (7.4 permil) pair from two AJ veins give consistent temperatures of $395 \pm 50^\circ\text{C}$ and $400 \pm 50^\circ\text{C}$, respectively. By assuming a temperature of 400°C , the pressure of trapping can be determined using the isochores calculated with the equation of state of Bowers and Helgeson (1983). The calculated pressure of trapping is between 2 and 3 kbar, which coincides with the usual depth of the brittle-ductile transition zone in the continental crust (Sibson, 1977). The temperature of 400°C is also used to calculate the oxygen and hydrogen isotopic composition of the vein-forming fluid. This fluid has a $\delta^{18}\text{O}$ value of 6 permil, and a δD value of -50 permil, which plots within the metamorphic water field (Figure 10).

The fluid inclusion and stable isotope geochemistry of the Rio vein fluids compare favourably with typical Archean mesothermal shear-zone hosted gold deposits (Robert and Kelly, 1987; Ho, 1987; Kerrich, 1989).

OTHER FLIN FLON AREA DEPOSITS

Fluid inclusion data indicates that fluids similar to those involved in the formation of the Rio deposit appear to be important in the formation of other structurally-controlled gold deposits in the western part of the Flin Flon Domain. The Tartan Lake deposit was formed from low salinity (2 to 7 wt.% NaCl equiv.),

H₂O-CO₂ fluids at a temperature of $350 \pm 50^\circ\text{C}$ (Fedorowich, 1989). Preliminary data collected from the Graham, Monarch, Henning-Maloney, Newcor, North Shear Zone, and IMC-Cain B occurrences, as part of this study, confirms the presence of H₂O-CO₂, low salinity fluids. The CO₂ density varies considerably, but this may have a bearing on the depth of formation of the occurrences.

The isotopic composition of the Tartan Lake and Graham vein fluids are plotted on Figure 10. Although the data for Tartan Lake does not rule out a magmatic fluid component, the overall variation between deposits underlines the probable importance of metamorphic waters in their formation.

GENETIC MODEL

A generalized model for the formation of the majority of the gold deposits in the Flin Flon Domain is shown in cross-

section in Figure 11. The oxygen and hydrogen isotopic compositions of the vein fluids indicate that the fluids were derived from dehydration and decarbonation reactions during regional metamorphism. These 300 to 400°C fluids probably leached gold from a variety of source rocks, and were then focussed into well-defined major structural zones. The fluids deposited gold within these zones at depths of about 6 to 10 km, correlative with the brittle-ductile transition zone. A change in the solubility of gold complexes due to pressure loss and associated unmixing of H₂O and CO₂ in dilatant zones probably causes gold deposition. The host lithology is not a significant control, because gold occurrences are found in virtually all lithologies in this area. The size of the deposits in the Flin Flon area may be related to the size and persistence of the host structure. Major regional shear zones are considered to be better exploration targets, because they are more likely to have focussed fluids from a more extensive source area.

BARREN VS. GOLD-BEARING VEINS

Characterizing the hydrothermal fluids involved in the formation of gold deposits using fluid inclusions and stable isotopes, have obvious ramifications in refining exploration strategies. A more direct exploration tool, however, may be the ability to distinguish between possible gold-bearing and barren quartz veins using stable isotopes and fluid inclusions. Unfortunately, such studies have tended to concentrate

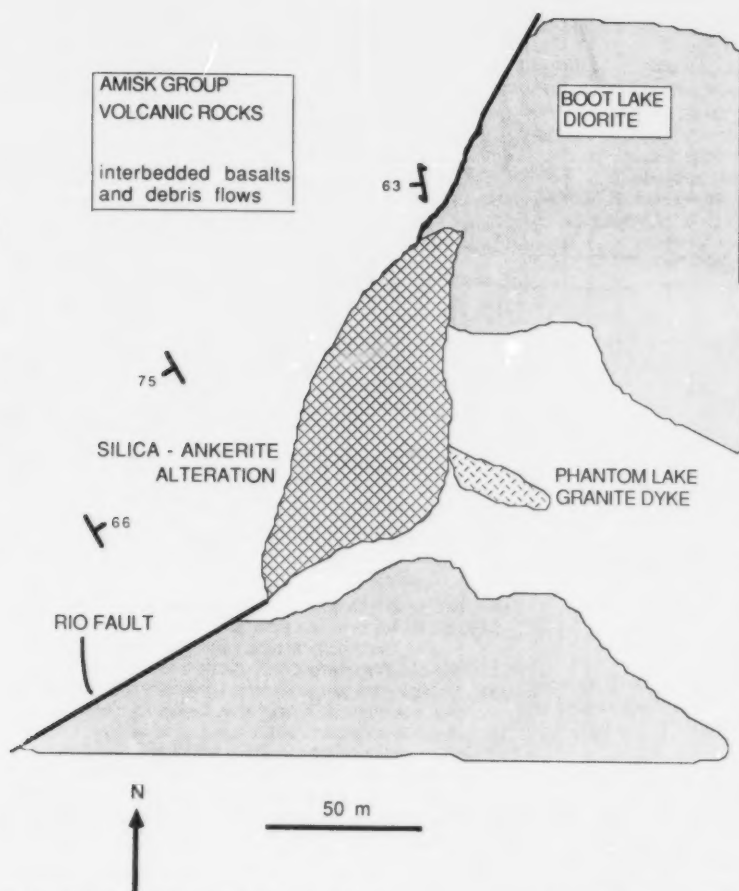


Figure 8 - Simplified geological map of the Rio deposit. Modified after Pearson (1984).

on the gold-bearing vein systems and comparable data for barren veins are lacking.

In this study, gold-bearing veins in the Flin Flon area are those that recently or historically have been trenched or mined, have elevated gold grades, and show evidence of a hydrothermal alteration envelope, whereas the barren veins are tension gash veins with no apparent mineralogical alteration halo. The $\delta^{18}\text{O}$ values of these quartz veins are shown in Figure 12, and supplement the data presented by Kyser *et al.* (1986). Although there is a greater range in the oxygen isotopic composition of quartz in barren veins, the overlap indicates that it would be extremely difficult to distinguish the two vein types using oxygen isotopes.

A complete fluid inclusion analysis of quartz veins is time-consuming, although a reconnaissance study of the fluid inclusion petrography can be conducted easily using normal thin sections. This may have potential as an exploration tool, because there ap-

pears to be a difference between gold-bearing and barren veins. In the gold-bearing veins in the Flin Flon area, the early primary and pseudosecondary fluid inclusions are dominantly CO_2 , or $\text{H}_2\text{O}-\text{CO}_2$ inclusions, with variable phase ratios within or between arrays of inclusions. If there are aqueous inclusions present, they are mostly secondary. In contrast, barren veins typically contain primary aqueous inclusions, and thus were formed from distinctly different fluids.

CONCLUSIONS

The character of the fluids involved in gold deposition in the Flin Flon area is important in refining genetic models based on geological and structural constraints. The majority of gold occurrences in the area are structurally controlled and formed during or after the major Hudsonian deformation events. Based on the fluid inclusion, and oxygen and hydrogen isotope investigations, gold precipitated at 300 to 400°C and depths of 6 to 10 km, from low salinity, $\text{H}_2\text{O}-\text{CO}_2$ fluids that were derived from dehydration and decarbonation reactions during regional metamorphism.

Gold precipitation probably

resulted from loss of stability of metal complexes accompanying sudden pressure loss as the hydrothermal fluid entered dilatant zones. Fluid-wall rock interactions might also have affected gold deposition locally. These occurrences are similar to Archean structurally-controlled, mesothermal gold deposits (Groves and Phillips, 1987).

In contrast, the Laurel Lake deposit on Missi Island, Amisk Lake, represents an earlier epigenetic gold mineralizing event that predates deformation. This deposit is distinctive in that it has a high Ag/Au ratio of 5:1, as compared to Ag/Au ratios of about 1:10 for the structurally-hosted gold occurrences; is not associated with a late structural feature; and is metamorphosed. The gold-sulphide-quartz veins at Laurel Lake were deposited from saline, CO_2 -poor hydrothermal fluids. Walker and McDougall (1987) considered Laurel Lake to be a shallow-level epithermal-type deposit, but the saline fluids are not typical of such systems. The calculated stable isotopic composition of the hydrothermal fluids is more consistent

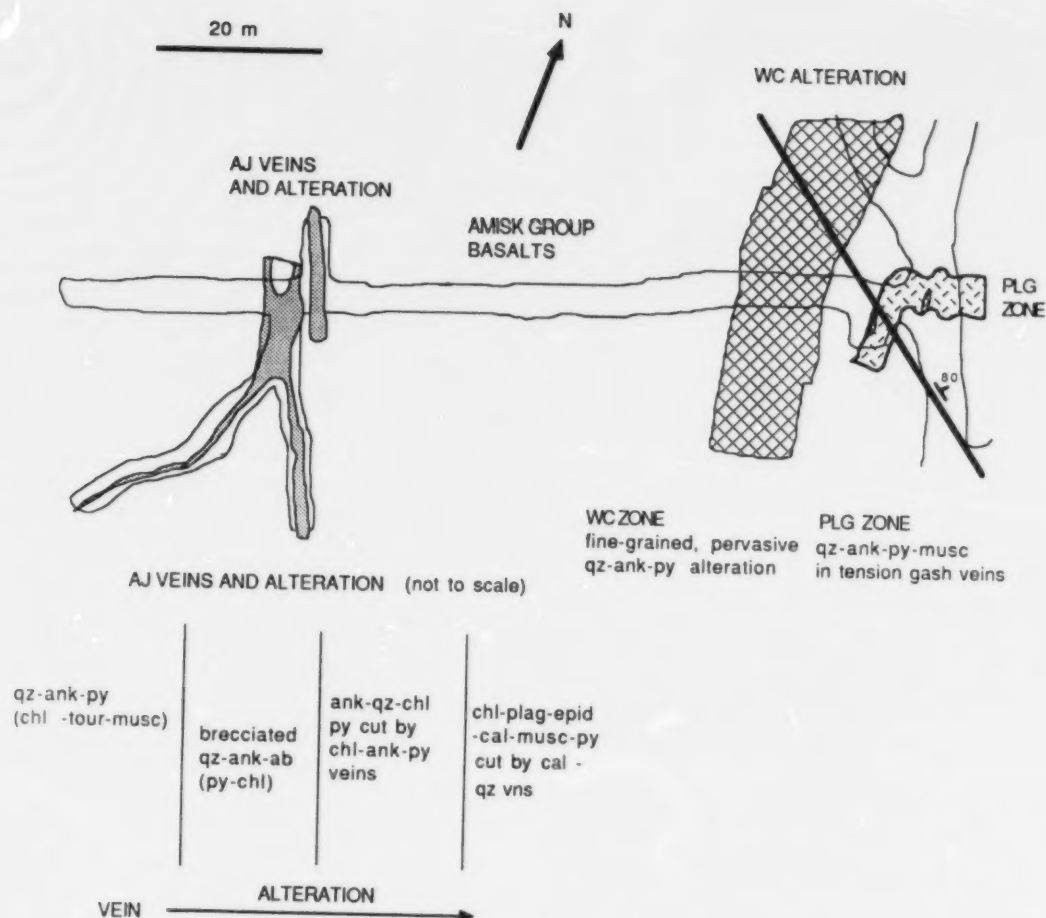


Figure 9 - Geological plan of the 215' Level, Rio deposit, showing the three different ore associations. Note that the alteration around the AJ veins is not always symmetrical. Mineral abbreviations: qz - quartz, ank - ankerite, py - pyrite, ab - albite, chl - chlorite, tour - tourmaline, musc - muscovite, plag - plagioclase, epid - epidote, cal - calcite.

with mineralization precipitated from heated seawater that had interacted with the volcanic rocks in the area. A magmatic fluid component is not apparent, making a direct relationship with the Missi Island Intrusion less likely. Isotopic age dating is required to determine whether the intrusion may still have acted as a heat source to drive the fluid circulation.

As an exploration tool the petrography of fluid inclusions in vein quartz could be useful in identifying veins that were deposited from fluids suitable for the formation of mesothermal gold deposits. Distinguishing barren from gold-bearing quartz veins in the Flin Flon area by measuring the oxygen isotopic composition of the quartz appears to have limited potential.

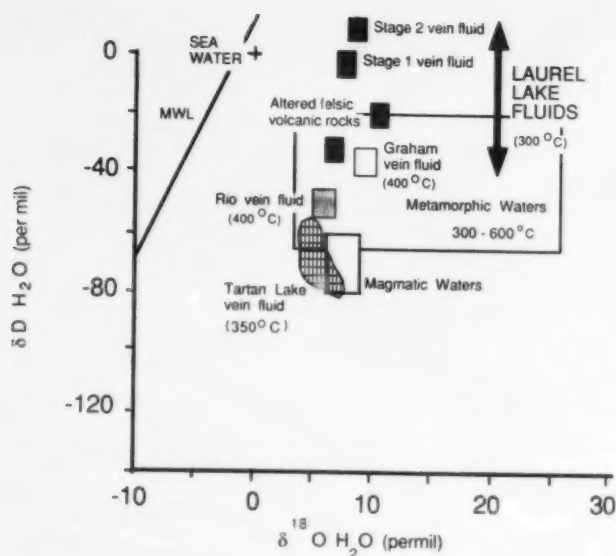


Figure 10 - The calculated oxygen and hydrogen isotopic compositions of fluids associated with the Rio, Graham, and Tartan Lake gold deposits fluids in comparison to the hydrothermal fluids involved in the formation of the Laurel Lake deposit (see Figure 5). Fluids from the Rio and Graham deposits have isotopic compositions typical of metamorphic waters, suggesting that they may be derived from dehydration reactions during prograde metamorphism. Source of data: Rio, Graham (this study), Tartan Lake (Fedorowich and Kerrich, in prep.).

Figure 11 - Model for mesothermal gold mineralization in the Flin Flon - Amisk Lake area showing the depth of formation of the Rio, Tartan Lake and Graham gold deposits. The mineralizing fluids were derived from metamorphic reactions, and focussed into regional scale structures. Combined structural, fluid inclusion, and stable isotope data suggest that the deposits formed at about 6 - 10 km, in the brittle-ductile transition zone, probably as a result of fluid mixing. The shear zones crosscut all the rock units in the area, and the deposit locations are not related to lithology on a regional scale.

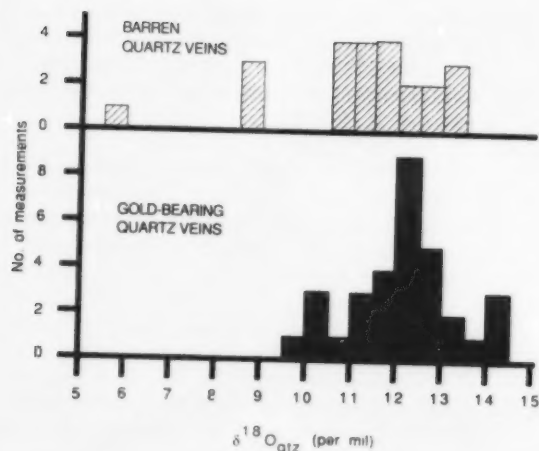
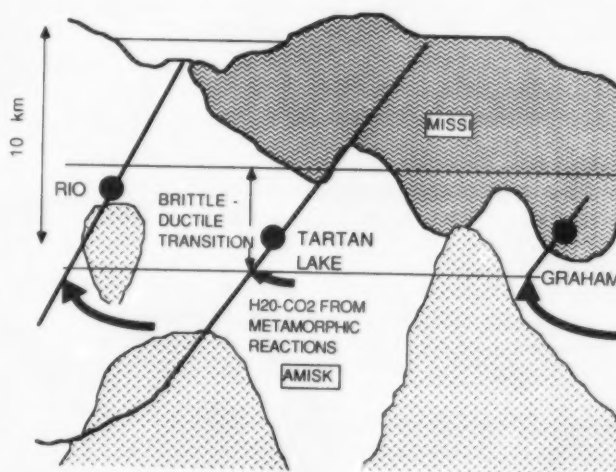


Figure 12 - Comparison between the $\delta^{18}\text{O}$ of barren and gold-bearing quartz veins in the Flin Flon - Amisk Lake area. Data from this study and Kyser et al. (1986).

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ACKNOWLEDGEMENTS

The authors would like to thank CAMECO and Husky Oil for permission to publish the Laurel Lake section of this paper. V. Sopuck, D. Jiricka, F. McDougall, M. Koziol, K. Dies, W. Coombe, M. Goulden, K. Zazulak and B. Hughes are thanked for logistical support and providing much useful information. D. Pezderic provided the expertise in the University of Saskatchewan Stable Isotope Laboratory. J. Fedorowich and T. Kotzer provided useful criticism of an early draft of this paper. C. Harper is thanked for a thorough review of the original manuscript.

This study is funded by CAMECO and NSERC through a University-Industry research grant.

THE URANIUM-GOLD-PLATINUM-GROUP ELEMENT ASSOCIATION IN THE GREATER BEAVERLODGE AREA, NORTHERN SASKATCHEWAN

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EXTENDED ABSTRACT

Fifteen different localities in the Greater Beaverlodge area were investigated for their potential to host platinum-group element mineralization (PGE). Twelve of these sites are well known uranium and uranium-gold mines or prospects. They include: the uranium-gold mineralization at the Nicholson numbers 2 and 4 zones and Fish Hook Bay; the Eagle, ABC, Cayzor, Martin Lake, Uranium Ridge and Leonard uranium mines; the Lodge Bay, Cornwall Bay, Eagle Group uranium showings, and the recently discovered Quartzite Ridge U-Au-PGE showing. Investigations of the Bax and Athona gold mines are also included in this study. These occurrences represent a new environment for PGE mineralization. Therefore, the purpose of the paper is to give a brief summary of the findings.

Of the 450 samples collected during this survey, anomalous levels of PGE mineralization were obtained only at the Nicholson numbers 2 and 4 zones, Fish Hook Bay, Uranium Ridge, Leonard Uranium Mine and Quartzite Ridge. All other localities have less than detection limit (2 ppb) concentrations of Pd and Pt, although high gold values can be found at most of these localities. Because the most notable concentrations are associated with hydrothermal pitchblende veins at Nicholson number 2 zone and Fish Hook Bay, these two deposits were chosen for further detailed geochemical, isotopic and mineralogical investigations.

Eight pitchblende occurrences investigated in the Nicholson Bay - Fish Hook Bay area clearly demonstrate that anomalous PGE concentrations are only to be found in the immediate vicinity of known mafic-ultramafic intrusions. From detailed investigations at Nicholson number 2 zone, the PGE and, to a lesser extent, gold are only found adjacent to a steep, easterly-dipping, north-east-trending fault zone that hosts thin, discontinuous carbonate-pitchblende veins. The mineralized fault zone occurs at the contact between unaltered, white and greenish-white dolomites, calc-silicates and quartzites of the Murmac Bay Group and grades into extensively hematized equivalents of the above. Vein pitchblende-carbonate mineralization in this zone ranges from a few centimetres to 2 m thick; however, the accompanying hematitic hydrothermal envelope can be up to 15 m thick.

Detailed geochemistry reveals some element specific characteristics of mineralized and non-mineralized rocks in this environment. Unmineralized rocks in the structural hanging wall within 10 m of the fault zone generally contain less than 2 ppb Pd, Pt and Au, 10 ppm U, Ti, La, Nb and 250 ppm Cl. The elements Se, Sb and Te are all present in concentrations less than the detection limit (0.20 ppm) whereas Bi and As have relatively high background values of approximately 0.8 ppm and 20 ppm respectively. FeO shows the most systematic decrease over this interval dropping from approximately 3.5 wt. percent to less than 0.80 wt. percent adjacent to the mineralized zone. Although not as systematic as FeO, the weight percent Fe₂O₃ increases noticeably towards the mineralized zone. A sharp increase in the concentration of Pd, Pt, Au, U, Ti, Se, Bi and Cl occurs at the contact of the hematized metasediments demarcated by the mineralized fault zone. The Pd, Pt and Au increase to 3660, 970 and 10973 ppb respectively, whereas the U and Ti concentrations increase to 1.20 and 3.56 percent respectively, which then drop to levels of

less than 0.1 percent over the next 0.50 m. Se, As and Bi better define the precious-metal-enriched interval with a ten to hundred fold increase in concentration. Also, chlorine concentration shows a three to ten fold increase in the precious-metal-enriched interval. The uranium-enriched zone is generally narrow (0.50 m); however, the precious metal interval can be up to 15 m thick. Although the highest precious metal endowment in the Nicholson number 2 zone is generally associated with the pitchblende veins, ore grade concentrations can be found in hematized footwall rocks that contain no macroscopic evidence of precious metal mineralization. The highest Pd, Pt, Au, Ru, Rh, Ir and Os concentrations obtained from the Nicholson number 2 zone were 57000, 38000, 130000, 280, 300, 63 and 18 ppb respectively.

Chondrite normalized PGE + Au profiles for mineralization from the Nicholson and Fish Hook Bay areas, as well as the newly discovered Quartzite Ridge mineralization, clearly indicate two different patterns characteristic of this camp and most likely of this style of mineralization (hydrothermal). The more common pattern has a very steep trend with marked Pd, Pt and Au enrichment and Os, Ir, Ru and Rh depletion. The other pattern has strong Pd, Pt and Au enrichment and moderate Os, Ru, and Rh enrichment. The two distinct patterns possibly represent different degrees of solubility of the PGE in hydrothermal fluids under different redox conditions. Compared to profiles from the Bushveld Complex the average Nicholson number 2 zone mineralization is similar in grade to the Merensky reef, whereas the high grade Nicholson mineralization, generally confined to the pitchblende veins, is far richer than the Merensky Reef in terms of Pt, Pd, Rh and Au. Analyses of unmineralized ultramafic samples from the Nicholson ultramafic complex disclosed an unusual chondrite normalized PGE profile. These samples are Ir- and Rh-enriched and Ru-, Pd- and Pt- depleted. It is believed that this pattern reflects the more refractory (less mobile/soluble) nature of elements like Ir and Rh relative to the more mobile Pd, Pt and Au. These patterns and the close spatial association of PGE-enriched pitchblende veins to mafic-ultramafic intrusions leaves little doubt that the platinum-group elements have been scavenged by hydrothermal fluids from local ultramafic source rocks.

Detailed mineralogical and paragenetic studies of the uranium-gold-PGE mineralization in the Nicholson and Fish Hook Bay areas has revealed a bewildering array of phases and paragenetic stages. Four stages are recognized: stage one and two produced the bulk of the uranium, carbonate, vanadate and PGE mineralization and, to a lesser extent, selenide mineralization; stage three produced most of the selenide, arsenide and sulphide mineralization; and stage four produced a variety of late supergene metal and sulphide phases as well as late stage iron oxides and sheet silicates. The main PGE- and, to a lesser extent, Au-mineralizing event occurred during stage 2. PGE and other precious metal phases identified include: oosterbosshite, froodite, stibiopalladinite, PdAuHgSb and PdAuAgSb phases, AuPd alloy, AuAgPd alloy, native Au, electrum, native silver and PGE-bearing selenides. Although no discrete platinum minerals were identified, electron microprobe analyses of Bi-selenides reveal that the platinum in the rocks can be accounted for by the high levels present in the Bi-selenides, cosalite and guanajuatite. Pt, Pd and Rh concentrations in guanajuatite range from 0.32-0.41, 0.06-0.25 and 0.01-0.24 wt. percent respectively whereas those for cosalite range from 0.44-0.46, 0.19-0.24 and 0.19-0.22 wt. percent respectively. It must be emphasized that it is only the Bi-selenides that contain significant PGE in solid solution.

The sulphur isotope signature of the sulphides from the U-Au-PGE environment is unlike that encountered in any of the other uranium-bearing systems. The sulphides, only present in trace amounts, are isotopically light, $\delta^{34}\text{S}$ -1.5 to -6.5 per mil, relative to the other environments which are all in the -1 to +11 per mil range, with a mean of approximately +3 per mil.

The presence of: a strong hematitic alteration halo; an increased $\text{Fe}_2\text{O}_3/\text{FeO}$ ratio approaching the mineralized zone; enhanced levels of chlorine in the mineralized zone; isotopically light sulphur; the abundance of selenides, in particular PGE-bearing Bi-selenides; radiometric dates for the uranium mineralizing event; and coeval radiometric dates for major crustal intrusive activity near these localities all help constrain a geological and thermodynamic model for this new type of PGE mineralization. The author proposes that the ore-bearing fluid was an oxidized brine derived from the basal portions of the overlying Athabasca Group clastic sequence. Phase chemistry and fluid inclusion work suggests that this mineralization formed at approximately 200°C at a log f_{O_2} of 10^{-38} to 10^{-28} in the pH range 4.5 to 6.5, and that the U, PGE and Au were transported as chloride complexes. It is inferred that the regional heat source for the hydrothermal system was provided by the Mackenzie igneous event (1265 Ma) which represents one of the most widespread episodes of mafic magmatism that has occurred in the North American continental crust.

Poster Papers

THE QUESTOR AIRBORNE DIURNAL MONITOR

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ABSTRACT

Observed aeromagnetic survey data are the summation of signals from the invariant background magnetic field, the attitude dependent magnetic field of the aircraft and the time and spatially dependent diurnal variations. In recent years, dramatic improvements have been made in magnetometer sensitivity and aircraft compensation using software techniques. Few improvements have been forthcoming in overcoming the problems of diurnal variation apart from using more base stations which are located closer to or within the survey area.

The spatial diurnal variations can be considered in two groups. The commonest daily variation arises from an overhead current system in the ionosphere which moves from east to west with the rotation of the earth. The second type of fluctuations are those associated with magnetic substorms and auroral current systems. Both types interact with the subsurface conductivity structure creating local distortions which will cause the observed fluctuation field to be spatially inhomogeneous. Field data from magnetometer arrays in the Canning Basin of Australia are presented to illustrate these phenomena.

Subtracting the variations recorded from a single base station is not necessarily adequate to remove the fluctuation field from the recorded total field airborne data everywhere in survey area.

Monitoring these variations along the survey line is now possible by integrating the difference of two independent magnetometers measuring the same field at different times. The time spacing is related to aircraft speed and sensor separation.

A simulation of the method using field data is presented along with preliminary data from the Questor Airborne Diurnal Monitor aircraft.

UNILOG - A COMPUTER BASED UNIFIED DRILL CORE LOGGING SYSTEM

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ABSTRACT

The UNILOG drill core logging program is a portable-computer based multi-commodity core logging database management system being developed by Cameco. The UNILOG program is the logical outcome of the use of the Cameco developed HP-1000 mini-computer based ULOG drill core logging program that has been in use since 1983.

Portable computers, printers and plotters are used at the exploration site. Drill core lithological, alteration, structural and sampling information is recorded using simple codes relating the features to specific depths in the drill hole. This coded data is subsequently entered into the computer data base using menu driven data input screens. With subsequent data input verification and editing, the database storage process is complete.

A full range of powerful user-defined database retrieval functions are available to allow for the display, storage and reporting of data that are of interest.

Graphical representations of the database are accomplished through the UNIGRAPH program module. Graphic capabilities include deviated sectional and plan view maps of drill hole lithological, alteration, structural and assay data. UNILOG generated database files can also be transferred to spreadsheets and other graphics programs. Anticipated future developments include the continued refinement of the program and database links to a geographic information system.

UNILOG is currently used on the majority of Cameco's exploration projects. It is an innovative exploration tool which has assisted in the standardization of core descriptions and allowed for a more reliable compilation, correlation and interpretation of large geological databases. Drill hole data can be thoroughly evaluated within the time frame of the current program, allowing the geologist to select successive drill hole locations based upon a more rigorous technical appraisal.

THE CHARACTERISATION OF CLAYS USING MICRO-REFLECTANCE SPECTROSCOPY

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ABSTRACT

Vibrational (infrared) spectroscopy can be used to characterise clays into the three major types, kaolinite, illite and montmorillonite. Transmission or DRIFTS techniques require the sample to be finely ground and mixed with KBr. The spectra are quantitative and the relative amounts of the clays present can be quickly and easily determined.

We have been developing the new technique of Micro-Reflectance Vibrational Spectroscopy to supplement these methods. Samples are either polished rocks or small particles mounted in resin and polished with isopropyl alcohol. They are initially characterized using conventional visible light microscopy. The spectra of positively identified portions of the sample, as small as $25 \mu\text{m}^2$, can be obtained by reflection from the polished surface. The conventional absorbance spectra are obtained from the reflection spectra by a Kramers-Kronig transform.

The success of vibrational spectral analyses in determining the composition of clay samples and in identifying the clays present in coal macerals and in carbonate and sandstone rocks will be discussed.

FLUORESCENCE SPECTRAL ANALYSIS AND HYDROCARBON EXPLORATION: EXAMPLES FROM PALEOZOIC POTENTIAL SOURCE ROCKS, SASKATCHEWAN

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ABSTRACT

Paleozoic, potential hydrocarbon source rocks are known to occur within several formations in the Saskatchewan portion of the Williston Basin. Organic-rich intervals within the Ordovician Yeoman and Mississippian Bakken Formations have been analyzed using fluorescence microscopy, emphasizing benefits of the technique to various aspects of hydrocarbon exploration. The Bakken and Yeoman Formations have both generated some liquid hydrocarbons from geographically and microfacies restricted zones.

The Yeoman Formation is considered incipiently to thermally mature where disseminated *Gloeocapsomorpha prisca* alginite generates lambda maximum values exceeding 600 nm. The effectiveness of the Yeoman Formation as a source rock is related to thermal maturity and the selective hydrocarbon generation from a specific type of *G. prisca* alginite microfacies. A disseminated alginite microfacies set within a dolomitic matrix is exceedingly more conducive to hydrocarbon generation than the microlaminated, 'stromatolitic' microfacies at equivalent levels of thermal maturity.

Anomalous generation of hydrocarbons in the Bakken Formation is defined by *Leiosphaeridia* alginite fluorescence spectra with lambda max. values greater than 590 nm. Such intervals in the Bakken are characterized by the unique association of hydrogen-rich kerogen with radioactive phosphatic nodules and fossils. This organic-mineral matter relationship appears to be fundamentally critical to the onset of hydrocarbon generation in the predominantly, thermally immature Bakken Formation.

INTRODUCTION

Exploration for hydrocarbons in sedimentary basins such as the Williston Basin has in the past, and at present, followed very conventional and monotonous exploration strategies. The most routinely used techniques include subsurface mapping of potential reservoir facies based on geophysical log- and core-defined lithologies, structural anomalies based on structural contour maps, and seismic profiling. Hydrocarbon exploration in many basins, and in particular frontier basins, has recently been supple-

mented and enhanced by detailed basin thermal history studies.

The distribution of hydrocarbons and the prevalence of particular hydrocarbons (i.e. liquid, and thermal and biogenic gas) in a sedimentary basin is for the most part a direct consequence of the basin's geothermal evolution. Understanding the thermal maturity or the maximum subsurface temperatures attained by organic-rich horizons (potential petroleum source rocks) through geological history, may be used to identify and predict zones of hydrocarbon

generation and subsequent definition of migration pathways.

The thermal history of a sedimentary rock is recorded in progressive organic chemical and molecular structural changes in sedimentary, disseminated organic matter (kerogen; Figure 1). These changes occur predominantly in direct response to geothermal heat regimes which have affected the sedimentary rock since deposition and subsequent burial. Analogous to chemical and molecular structural changes in source rock kerogen is the expectation that coal rank will increase with depth through a borehole. Consequently, the optical properties of specific types of kerogen (e.g. vitrinite) progressively change in response to the thermal history of a

sedimentary rock. Optical microscopy methods are used (in conjunction with organic geochemistry) by many petroleum exploration teams when assessing thermal maturity, quality, and hydrocarbon-generating ability of potential hydrocarbon source rocks (Figure 2). The main emphasis of this paper will be the introduction of a specific organic petrological technique (fluorescence spectroscopy) as applied to petroleum exploration. The method will be illustrated using data collected from two stratigraphic horizons in the Williston Basin, Saskatchewan.

METHODS OF ORGANIC PETROLOGY

The volume of organic matter in any given sedimentary rock is a direct result of the biomass productivity

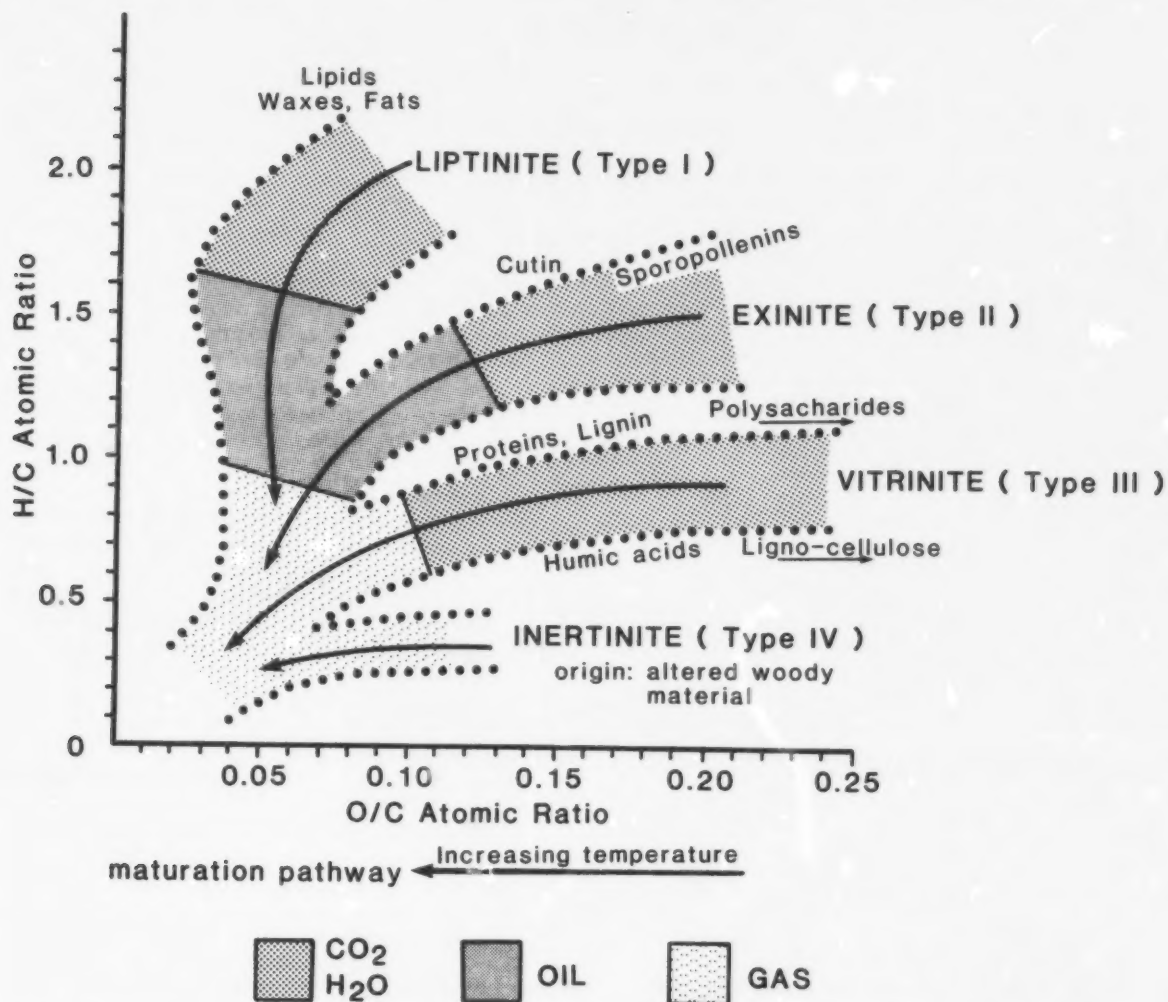


Figure 1 - The origin and general chemical composition of the four main types of kerogen, expressed in terms of H/C vs O/C. The changes in the chemical ratios and evolved products from diagenesis, catagenesis, through metagenesis are shown along the paths of thermal maturation (from Brooks, 1981).

in the paleodepositional area and the effectiveness of the water conditions to inhibit oxidation of organic material (i.e. anoxic vs. oxic Eh conditions). The preserved fraction of organic matter in sedimentary rocks is referred to as kerogen, which comprises a variety of unique microscopic organic components generally referred to as macerals (Figure 1).

Maceral identification and characterization utilize polished rock pellets observed through high power oil immersion objectives using white and ultra-violet incident light. The basis for classification of macerals in potential source rocks has been largely extracted from coal petrographic nomenclature. Modifications to coal maceral classifications are based on the

geological age and general depositional environment of the source rock interval. These two factors control the distribution of organic components which typically occur in organic-rich sediments. Modifications attributed to geological age stem from the evolution of marine and terrestrial organisms. For example, resinous material (resinite) derived from conifer trees would not be found in Cambrian through Devonian rocks; likewise remains of organic fossils such as chitinozoa would not be present in potential source rocks of Cretaceous age. An example of classification modifications attributed to the depositional environment is the inclusion of secondary macerals such as the bituminite spectrum of microbially degraded organic matter.

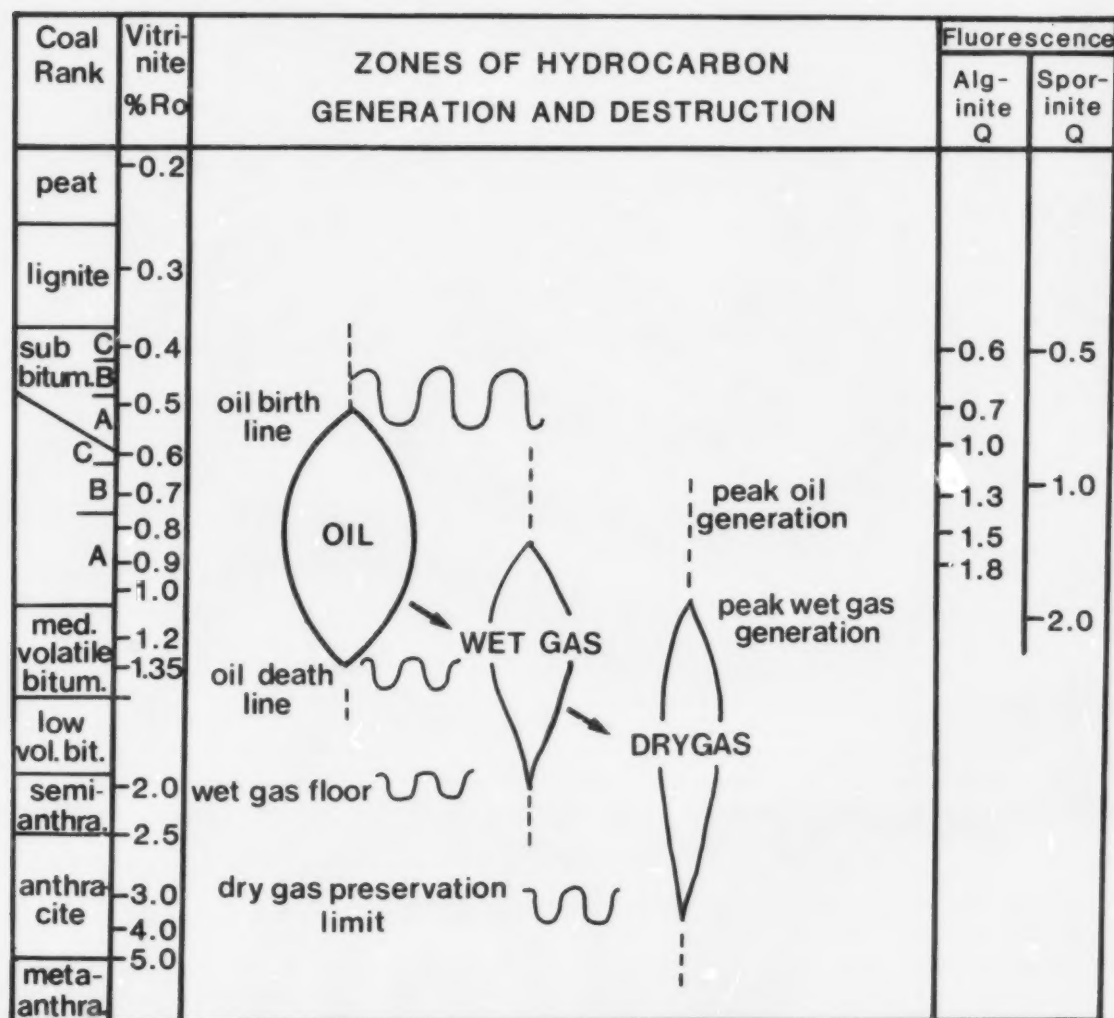


Figure 2 - Correlation of universally accepted optical parameters used by organic petrologists and petroleum geologists to define source rock thermal maturity levels in relation to stages of hydrocarbon generation (from Teichmüller, 1986). %Ro = percentage reflectance in oil ($\eta = 1.5148$); Q = Red/Green Quotient.

Ultra-Violet/Fluorescence Spectroscopy

Potential hydrocarbon source rocks generally contain traces to concentrated amounts of hydrogen- or sporopollenin-rich kerogen, originally derived from algae, spores, pollen cuticles, resins, bacteria, etc. (or anaerobically degraded products thereof). During exposure of hydrogen-rich macerals to ultra-violet energy (365 nm), certain portions of the organic molecules (chromophores) emit photons of light (i.e. they fluoresce) as a result of the transition from an excited electronic state to a ground state of lower energy (Bertrand *et al.*, 1986; Khavari-Khorasani, 1987). The visible light wavelengths (400-700 nm), which represent part of the spectrum emitted by fluorescing macerals during the transition to a more stable energy state, can be characterized spectroscopically.

The relationship between fluorescence of organic matter and depth/temperature is primarily a function of thermally induced changes in the organic chemistry and molecular structure of hydrogen-rich macerals (e.g. decarboxylation, dehydrogenation, development of a relatively more aromatic or cyclic molecular structure, generation and release of short chain or liquid hydrocarbons).

The effect of increasing thermal maturation on hydrogen-rich macerals is reflected in a shift of the maximum wavelength position of greatest fluorescence (λ_{max}) from blue to red (400-700 nm) (Figure 3). The spectral parameter Red/Green Quotient (R/G=Q) (Figure 3) is also used to characterize curves generated for fluorescing macerals.

Figure 4 illustrates the wavelength shift for two hypothetical source rocks which have undergone different burial and thermal histories. In potential source rock A the fluorescence of an alginite maceral subjected to 2000 m of burial and a maximum temperature of 60°C for 40 ma, would emit a λ_{max} between 420 and 460 nm. Potential source rock B alginite (Figure 4), of greater thermal maturity, subjected to 2000 m of burial and a maximum temperature of 100°C over 150 ma, would emit fluorescence energy with a λ_{max} probably beyond the 620 nm position.

Fluorescence microscopy is currently being used to investigate the variation in thermal maturity levels of potential Paleozoic source rock horizons in the Saskatchewan portion of the Williston Basin. The two stratigraphic intervals used as working examples in this introductory paper to the method are of Upper Ordovician and lowermost Mississippian age (Figure 5).

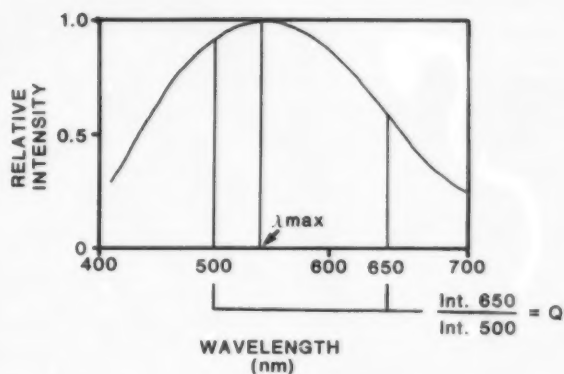


Figure 3 - Determination of fluorescence spectral parameters λ_{max} and Red/Green Quotient (R/G=Q), for emissions from hydrogen-rich macerals such as alginite.

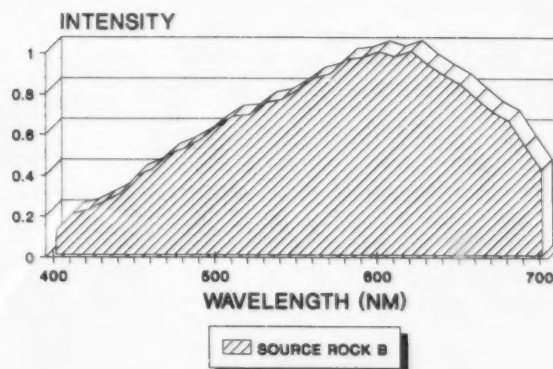
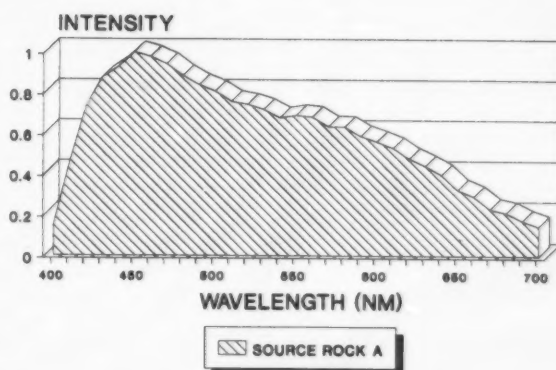


Figure 4 - A comparison of fluorescence spectra generated from alginite within two hypothetical, potential hydrocarbon source rocks, which have undergone different geothermal and burial histories. Source Rock A alginite spectra is typical of thermally immature strata (minimal hydrocarbon generation); Source Rock B alginite spectra is typical of thermally mature strata (hydrocarbon generation).

Application For The Petroleum Geologist

Organic petrology can provide valuable information about the geological and economic significance of a potential hydrocarbon source rock, such as: (1) whether the kerogen is conducive to liquid or thermal gas generation; (2) whether there is any indication of biogenic gas generation; (3) depositional environment interpretation, particularly where the reservoir rock is positionally associated with the source rock; (4) assessment of the thermal maturation level of the source rock and whether hydrocarbon generation has occurred; and (5) provide conclusive microscopic evidence for primary and secondary migration of hydrocarbons. This paper will exemplify some of the above points using two potential source rock intervals from the Williston Basin, Saskatchewan.

EXAMPLES FROM PALEOZOIC OF SASKATCHEWAN

Upper Ordovician Yeoman Formation

The organic-rich interval (referred to as kerogenite by Kendall, 1976 and kukersite by Osadetz *et al.*, 1989) in the Yeoman Formation (Figure 5) was deposited as part of a carbonate to evaporite cycle, specifically in a subtidal depositional environment (Kendall, 1976; Osadetz *et al.*, 1989; Stasiuk and Osadetz, in press). Lithologically the source rock is somewhat variable but can generally be classified as a bituminous lime mudstone.

Organic Petrology

The major organic component or maceral in the kerogenite intervals of the Yeoman Formation is an oil-prone, marine alginite, derived from the organism *Gloeocapsomorpha prisca*, Zalessky 1917. Associated with the alginite are minor amounts of acritarchs, microspores, and chitinozoa.

G. prisca occurs in two distinct, interlaminated, textural habits: disseminated and microlaminated microfacies. The disseminated microfacies is characterized by cup-like agglomerations of isolated *G. prisca* (10-70 μm in diameter) floating in a matrix of micritic dolomite (Plate 1a). Kerogen in this microfacies generally constitutes from 5-25 percent of the total volume. The associated dolomite rhombs range from 10 to 80 μm in diameter. Petrographically this organic microfacies appears to be the most effective Yeoman Formation hydrocarbon source interval, even though in relative terms it is not the most organic-rich, Yeoman microfacies, and would probably be defined as such by Rock Eval methods.

The second microfacies is characterized by distinct microlamination and 'stromatolitic' structures. The

textures from this microfacies are described in detail by Stasiuk and Osadetz (in press). Associated mineral matter occurs as isolated or lenses of dolomite rhombs in predominantly organic lamination (generally <20 percent mineral by volume). The laminated alginite textures in this microfacies (e.g. pustules, algal heads and pinnacles) are strikingly similar to those produced by stromatolite-forming, cyanobacteria (blue-green algae) in Holocene, subtidal to intertidal depositional environments such as Andros Island, Bahamas (Black, 1933) and the Trucial Coast, Persian Gulf (Park, 1977).

Thermal Maturation and Recognition of Oil Generation

The main interest and benefit of an organic petrological source rock study is the conclusive identification of intervals which have generated hydrocarbons. Quantification of fluorescence emissions from *G. prisca* alginite (R/G quotient, lambda max.) and visual microscopic evidence of liquid and solid hydrocarbons are currently being used to define geographic locations of kerogenite oil generation.

Lambda max. for *G. prisca* alginite in the disseminated microfacies ranges from 590 nm (1-25-23-16w2; 1714.1 m) to 650 nm (1-14-1-17w2; 3102.6 m). Associated R/G quotient values range from approximately 1.30 in the least thermally mature Yeoman Formation (e.g. 3-14-8-20w2; 2577.1 m) to 2.00 for the most mature (e.g. 1-14-1-17w2; 3102.6 m). A comparison of fluorescence spectra from thermally immature and thermally mature disseminated *G. prisca* (Figure 6) illustrates an obvious difference between the properties of Ordovician source rock alginite which have not generated oil and intervals which have.

The lambda max. values for 'stromatolitic' alginite microfacies range from 560 nm (3-14-8-20w2; 2577.1 m) to 630 nm (1-14-1-17w2; 3102.6 m); R/G quotient ranges from 0.70 (3-14-8-20w2; 2577.1 m) to 2.10 (1-14-1-17w2; 3102.6 m) (Figure 7). There is no microscopic evidence for generation of hydrocarbons in the 'stromatolitic' *G. prisca* alginite microfacies, even at the highest levels of thermal maturation.

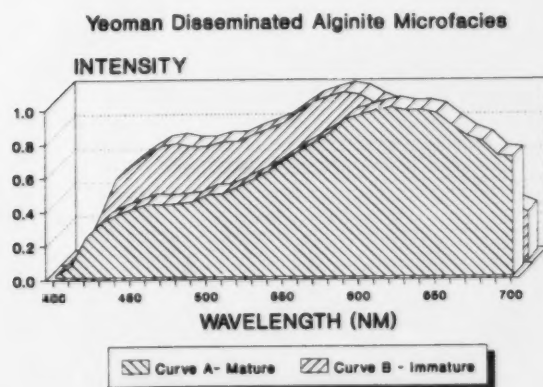
Preliminary results indicate that the generation of hydrocarbons from kerogenite intervals of the Yeoman Formation is directly dependent on the preserved growth habit or microfacies of *G. prisca* alginite. For example, the microlaminated or 'stromatolitic' microfacies has not generated hydrocarbons at locations where it is quite evident that the associated disseminated microfacies has (e.g. 3-26-4-20w2, 2832.1 m; Plate 1a). Reasons for this are still under investigation, but from a source rock evaluation and exploration perspective, it is vital to

bons. The Bakken Formation consists of lower and upper members of black to brownish-black, fissile, organic-rich shales separated by a coarser clastic member interpreted by Kent (1987) as an intertidal deposit because of the sedimentary structure assemblage and the presence of ooids.

Organic Petrology

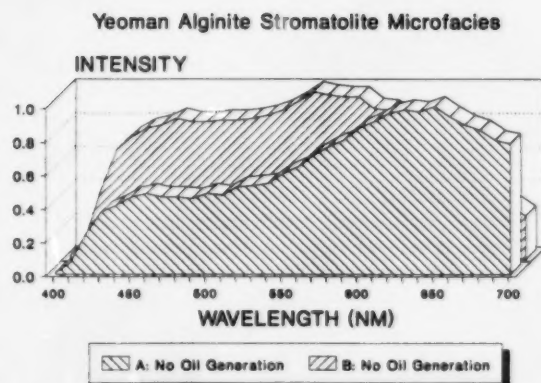
The kerogen assemblage of the Bakken Formation can be extremely variable resulting not so much from the derivative biomass of the macerals, but from penecontemporaneous and early diagenetic alteration of the organic matter resulting in a complex assemblage of degradation products (mainly bituminites). As detailed petrology is not the emphasis of this paper and, for the sake of simplicity, the organic matter in the Bakken shales has been broadly grouped into 'degraded' and 'non-degraded' categories.

Macerals within the 'non-degraded' category consist predominantly of marine alginite (*Leiosphaeridia* and *Tasmanites*), with lesser amounts of acritarchs, terrestrial sporinite, and minor amounts of floral-derived vitrinite and inertinite macerals. The 'degraded' group of macerals consists mainly of the enigmatic bituminites characterized by a spectrum of microscopic morphologies, surficial textures, mineral matter-organic matter associations and optical properties. Hypotheses as to the origin of the various varieties of bituminite include: (1) anaerobic, microbial degradation products originally derived from a mixture of higher plant lipids, algae, and possibly bacteria (Stach *et al.*, 1982); (2) oxidation of or-



Curve A: 1-25-23-16w2; 1714.1m
Curve B: 1-14-1-17w2; 3102.6m

Figure 6 - Fluorescence spectra generated from *G.prisca* alginite, disseminated microfacies, Yeoman Formation. Curve A represents a thermally immature source rock interval; Curve B represents a thermally mature source rock interval associated with unequivocal microscopic evidence of liquid hydrocarbon generation.



A: 3-14-8-20w2; 2577.1m
B: 1-14-1-17w2; 3102.6m

Figure 7 - Fluorescence spectra generated from *G.prisca* alginite 'stromatolitic' microfacies in the Yeoman Formation; note the wide range in spectral characteristics. At either extremity, petrographic evidence for hydrocarbon generation from this textural form of alginite is minimal.

ganic matter during deposition (Teichmüller and Ottenjann, 1977) and; (3) the residual product remaining after the metabolic utilization and conversion of hydrogen-rich kerogen to CH_4 by methanogenic bacteria in an anaerobic, and dissolved sulphate-free, post-depositional environment (Stasiuk and Goodarzi, 1988). The origin of bituminite assemblages in the Bakken Formation is under investigation utilizing both organic petrology and Micro-Reflectance Fourier Transform Infrared Spectroscopy.

The alginite macerals, derived from *Leiosphaeridia* and *Tasmanites*, have been used to assess the thermal maturity levels of the Bakken using fluorescence spectral analysis.

Thermal Maturation and Recognition of Oil Generation

Extensive liquid hydrocarbon generation has not been identified within either the upper or lower member of the Bakken Formation. However, at a few locations anomalous hydrocarbon generation has been detected where hydrogen-rich kerogen occurs associated with uranium-rich (?), phosphatic fossils and nodules, and detrital radioactive metallic minerals.

The fluorescence spectra of *Leiosphaeridia* alginite in the Bakken Formation is relatively consistent throughout Saskatchewan and only small deviations exist in the predominant low levels of thermal maturity. Spectral analysis of *Leiosphaeridia* from thermally immature locations generate lambda max.

values in the range of 440 to 480 nm, with R/G quotients ranging from 0.40 to 0.65 (Figure 8).

Where phosphate and radioactive detrital minerals are associated with alginite (Plate 1b), the fluorescence spectra generated (Figure 9) are distinctly different from those produced by alginite dispersed within typical Bakken mineral matter. Lambda max. ranges from 590 to 620 nm and the R/G quotient ranges from 0.80 to 1.70. It is clear from microscopic evidence that localized hydrocarbon generation has occurred at these anomalous locations (Plate 1b).

SUMMARY

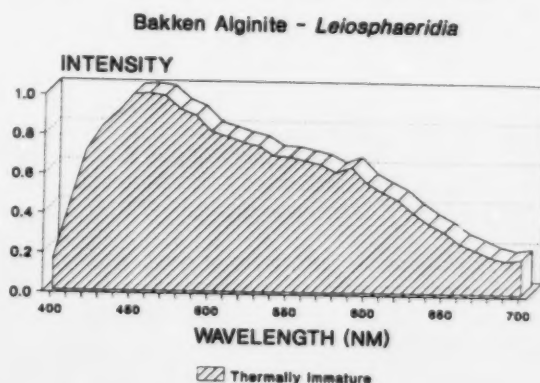
Preliminary results strongly suggest that organic petrology studies of potential, Paleozoic source rocks in the Saskatchewan portion of the Williston Basin will be able to define subsurface zones of hydrocarbon generation. In particular, fluorescence microscopy and emission characterization of hydrogen-rich macerals such as alginite appears to be a valuable technique.

The Mississippian Bakken and Ordovician Yeoman Formations have both generated at least some liquid hydrocarbons within somewhat restricted geographical and microfacies zones. Anomalous generation of hydrocarbons in the Bakken is defined by *Leiosphaeridia* alginite fluorescence spectra with

lambda max. values greater than 590 nm. Such intervals in the Bakken that have generated hydrocarbons contain the unique association of hydrogen-rich kerogen with radioactive, phosphatic nodules and fossils. This relationship appears to be fundamentally critical to the onset of hydrocarbon generation in the Bakken Formation.

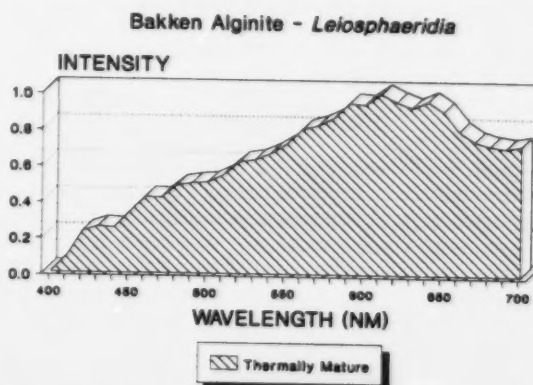
The effectiveness of the Yeoman Formation as a source rock is related to thermal maturation and, perhaps equally as important, selective hydrocarbon generation from a specific type of *G. prisca* alginite microfacies. A disseminated alginite microfacies within a dolomitic matrix is exceedingly more conducive to hydrocarbon generation than associated microlaminated 'stromatolitic' microfacies in regions of greatest thermal maturity.

The emphasis of this paper has been to promote the supplemental use of fluorescence microscopy in hydrocarbon exploration utilizing the concept of thermal maturation and microscopic recognition of hydrocarbon generation from alginite macerals. This represents only a minor aspect of a much larger study currently in progress. In addition, controls on source rock accumulation, depositional environment interpretations and identification of primary migration zones are being gleaned and are expected to provide insight into the generation of hydrocarbons from Paleozoic source rocks in Saskatchewan.



Location: 8-20-4-14w2; 1971.14m
Lambda max. = 460nm; R/G Q = 0.39

Figure 8 - Fluorescence spectra generated from *Leiosphaeridia* alginite within thermally immature Bakken Formation shale.



Location: 16-10-3-25w2; 2087.9m
lambda max. = 610 nm; R/G Q = 1.79

Figure 9 - Fluorescence spectra generated from *Leiosphaeridia* alginite which has been subjected to radioactive decay from U-rich(?), phosphatic nodules and fossil debris.

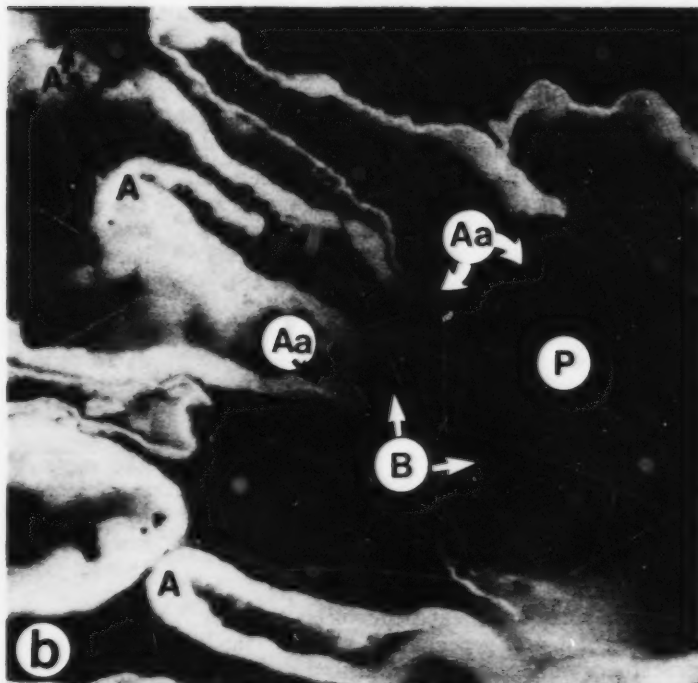
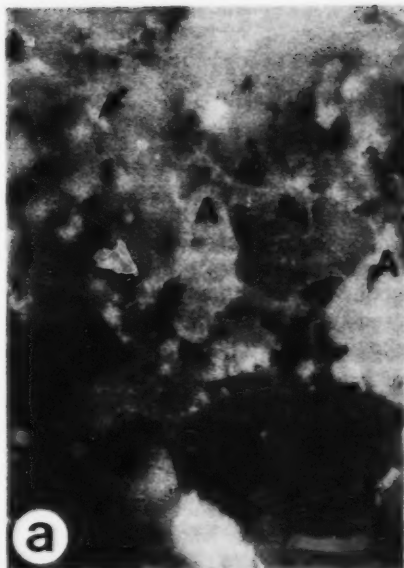


Plate 1 - Photomicrographs of alginite illustrating hydrocarbon generation and the transformation from a solid maceral component to liquid hydrocarbons, (oil immersion objectives, incident, fluorescent light, x2000). a) *G. prisca* alginite (A) in a 'softened state' typical of thermally mature, Yeoman Formation, disseminated microfacies. Hydrocarbons generated from the alginite are situated in porosity and intercrystalline regions, (indicated by arrows). b) *Leiosphaeridia* alginite (A) from the Bakken Formation associated with U-rich (?), phosphatic material (P). Note the radioactively altered zones of the alginite (Aa) where hydrocarbon generation has taken place. The shale matrix is heavily bitumen stained (B) proximal to the altered alginite.

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ACKNOWLEDGEMENTS

Project funded by Office of Energy Research and Development, Energy Mines and Resources, Canada; O.E.R.D. Project 6.1.1.04. The authors would like to thank Dr. A.R. Cameron, Geological Survey of Canada, Institute of Sedimentary and Petroleum Geology, Calgary, Alberta, for critically reviewing the manuscript.

MICRO FT-IR SPECTROSCOPY OF COAL MACERALS IN THE PALEOCENE LIGNITES FROM THE RAVENSCRAG FORMATION, SOUTHERN SASKATCHEWAN

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ABSTRACT

Large quantities of lignite are being mined from the Paleocene Ravenscrag Formation in southern Saskatchewan. They were deposited in deltaic and alluvial deltaic environments. The Ravenscrag lignites overlie Upper Cretaceous non-marine sands, silts and clays.

Coal is developed by the transformation of plant material in the peat deposits, influenced by a series of chemical and physical factors. Thus the different coal macerals (huminites, liptinites and inertinites) are derived from woods, leaves, spores and pollen grains of the peat-forming vegetation. Coal macerals have different chemical compositions, especially in low rank coals, and differ considerably in their reactivity during conversion processes. Micro FT-IR spectroscopy, which can analyse sample areas as small as 5 μm by 5 μm , can be used to determine the functional groups present in individual coal macerals.

Five lignite samples from the Hart seam (Willowbunch coalfield) and the Souris and Estevan seams (Estevan coalfield) were used in Micro FT-IR analyses. The Hart seam coal is of lower rank than the Souris and Estevan samples. Our results indicate that the eu-ulminite A macerals are chemically more complex than the eu-ulminite B macerals. The latter have more condensed aromatic structure and a lower oxygen content. A decrease in oxygen, nitrogen and hydrogen content with an increase in carbon and aromaticity has been attributed to an increase in coal rank. This is also reflected in the similarities in spectra between the eu-ulminite A of the Estevan seam and the eu-ulminite B in the Willowbunch coalfield. A strong band at 1335 cm^{-1} representing aromatic ethers and phenols is found only in corpohuminites. These perhaps represent the phenolic metabolic products that are built into the humic acid. Inertinites in the two coalfields are mostly similar. However, certain semifusinites are closer to the huminites than other inertinites and are perhaps, partially reactive. The chemical information from micro FT-IR spectroscopy of coal macerals can be used to supplement petrographic data to predict the suitability of coal seams for conversion processes.

METALLOGENETIC MODELS AS EXPLORATION TOOLS

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ABSTRACT

Mineral exploration is based on the systematic determination of various parameters which can be used to locate anomalies that reflect the presence of potential economic mineralization within the host environment. The search for these anomalies is a high-risk financial endeavour. To reduce the magnitude of this risk, the best technical tools must be utilized.

The nature of the tools to be used depends on the type of mineralization sought and on the metallogenetic model. A metallogenetic model is formulated by compiling and interpreting the essential characteristics of a group of similar deposits, assuming a fundamental unifying concept of genesis. The framework of this model is defined by deposit morphology and mineralization, structural/metamorphic relationships, host-rock mechanics, and lithogeochemical/mineralogical data. The most important aspect of the model for the exploration geologist is the description of the relationships between mineralization and the host rocks, in both time and space.

In the case of unconformity-type uranium deposits, the diagenetic-hydrothermal metallogenetic model relates uranium mineralization to diagenetic processes operating within the Athabasca Group sandstones. Use of this model suggests possible locations of the mineralization target, form(s) of mineralization, patterns of host-rock alteration and geochemical dispersion, and structural/metamorphic associations.

Mineralogical exploration targets suggested by the model are zones of brecciation with loss of coherence and residual clay mineral enrichment, and presence of characteristic clay and accessory minerals within the host-rock alteration halo. Lithogeochemical anomalies consist primarily of those major and minor elements that reflect the mineralogical alteration. The model also predicts deposit and alteration halo dimensions and topology which can dictate decisions concerning drill hole placement and length. Bedrock sampling and drift prospecting are suggested reconnaissance survey methods. Mineralogical analyses plus trace/minor element geochemical analyses are recommended for elucidating the dispersion halos caused by the mineralization process.

The model suggests that the primary structural target is the intersection of regional basement lineaments with the sub-Athabasca Group unconformity. Tectonic controls and lithological competency contrasts of basement rocks have focussed fracturing in the more massive, felsic units. This has promoted fluid movement within these units and permitted sandstone-basement fluid interaction. Field mapping and geophysical methods are powerful tools for use in delineating regional structural and lithological patterns.

While metallogenetic modelling is a valuable tool in mineral exploration, it must not be used blindly. A given model should not be used just as a rationalization of the available data, but should be revised or discarded on the basis of new data or interpretations.